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VORTEX FORMATION IN A CYLINDRICAL TANK

A THESIS

Presented to

the Faculty of the Graduate Division

By

Charles Ray Ferguson

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Chemical Engineering

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VORTEX FORMATION IN A CYLINDRICAL TANK

APPROVED:

Date Approved by the Chairman: 12/4/58

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NOMENCLATURE

d	inside diameter of discharge pipe, ft.
D	inside diameter of tank, ft.
g	acceleration due to gravity, ft.^{2}/sec.
h_c	height of water in tank when vortex reaches pump suction, ft.
h_f	height of formation, ft.
h_o	initial water height, ft.
L	length, ft.
M	mass, lb. mass
P_c	pump suction pressure at h_c, psia
P_f	pump suction pressure at h_f, psia
Q_C	volumetric flow rate through copper tubing, GPM
Q_{Rc}	reduced volumetric tank discharge rate when vortex reaches pump, GPM
Q_{Rl}	reduced volumetric tank discharge rate when liquid level is one foot, GPM
Q_T	volumetric flow rate from tank, GPM
q	volumetric flow rate from tank, ft.^{3}/sec.
T	torque, lb. mass, ft.^{2}/sec.^{2}
T_L	water temperature, ^oF
t	time, sec.
μ	water viscosity, lb., mass/ft.-sec.
ρ	water density, lb. mass/ft.^{3}
θ	time, sec.

ABBREVIATIONS

n.v.	no vortex formed
n.c.	vortex did not reach pump
n.a.	flow not affected by vortex

SUMMARY

Vortex formation in incompressible fluid media has received renewed interest in the past few years. The possibility of vortices affecting tank discharge coefficients and pump performance has become a problem of great concern where high rates of flow are required. It seemed profitable, therefore, to investigate a number of the factors affecting vortex formation and to determine if preventative measures could be taken to minimize the resulting difficulties.

The apparatus used in this investigation consisted of a plastic cylindrical tank nine feet high and one foot in diameter connected to a rotary pump by glass piping. Consideration of the physical situation and a dimensional analysis indicated that the height of vortex formation to the tank diameter ratio was a function of seven dimensionless groups. It was found that only two of these seven groups were significant in this investigation, the result being

$$\frac{h_f}{D} = \phi \left(\frac{T}{q\mu}\right) \left(\frac{h_o}{D}\right)$$

This relation is represented by a series of graphs of $(\frac{T}{q\mu})$ vs. $(\frac{h_f}{D})$ using $(\frac{h_o}{D})$ as a parameter.

Once initiated, vortices developed rapidly and reduced pump performance at high flow rates. The effect on discharge rates is shown graphically.

Circular baffles were effectively employed to eliminate vortex formation in the tank with a flat bottom.

CHAPTER I

INTRODUCTION

The purpose of this study was to investigate vortex formation in an incompressible fluid in a cylindrical tank.

Most of the theoretical work done on this subject has been conducted in the fields of compressible media. Aerodynamists have studied vortices during the high speed flow of air across airfoils to improve the aerodynamic cleanliness and stability of supersonic aircraft. Meteorologists have been concerned with vortex formation in the atmosphere to better understand and predict tornadoes, hurricanes, and typhoons in attempts to minimize their yearly destruction. Coriolis force is a contributing factor in these vortex formations.

Recently, renewed interest has developed in the possibility of vortex formation in liquids draining from tanks. Missile designers are concerned with the possibility of vortices effecting liquid discharge rates from tanks feeding high consumption rocket engines. However, at the present time, little is known about vortex occurrence and elimination of the resulting difficulties. Therefore, the present study of vortex formation in cylindrical tanks was undertaken.

An examination of the literature revealed that most of the investigations in this field were undertaken during the past 10 years. Studies of free vortex flow through orifices were conducted in 1949 at the University of Iowa by Posey and Hsu[1]. Tests were made on a 4 inch sharp-edged circular orifice in the center of the bottom of a 6 foot diameter tank. Tangential flow was directed into the tank through four 1-inch pipes equally spaced around the circumference, and radial flow was guided in through a false bottom directly below these jets. A constant head of 1.63 feet was maintained with the variables being the tangential and radial approach velocities. The orifice coefficient of discharge was expressed as a function of the ratio of these velocities. The reduction in discharge due to the vortex varied from 5 to 75 per cent.

In 1951, Li[2] conducted studies of a single vortex in a real fluid at the University of California. Tests were conducted in a set of rotating glass cylinders. The outer cylinder was 2 feet high, had an inside diameter of 11 inches, and was connected by wooden strips to an inside cylinder having an outside diameter of 9 inches. Water was introduced in the annular space between the tanks and given a tangential velocity component by the wooden connectors. A constant head was maintained in the tank with the speed of rotation and the rate of discharge being varied. The shape of the water surface was recorded photographically and tangential velocities were computed from the measured surface slopes. With these data, constants for the Navier-Stokes equations of motion were determined for a single vortex in a real fluid and an ideal fluid. By comparing his theoretical and experimental results, Li was able to recognize the importance of viscosity in vortex flow.

In 1956, Stevens and Kolf[3] conducted a series of experiments at the University of Wisconsin on vortex flow through horizontal orifices. The studies consisted of tests made in two different tanks and the effect of vortices on discharge rates. Initial tests were made in a 12 foot diameter tank 2 feet high with an orifice plate in the center of the tank bottom. Vortex profile measurements were made with a moving point gage mounted on an Aluminum I beam. Water was introduced tangentially through a series of guide vanes concentric with the orifice opening. With the aid of these vanes the water could be directed toward the orifice opening with any desired approach angle. A second series of tests were conducted in a 6 foot diameter tank 3 feet high in order to extend the data with respect to head and boundary proximity. Kolf determined that vortex formation reduced the flow through the orifice from 13 to 73 per cent below the discharge with no vortex present. Stevens had made use of the reduced flow encountered in vortex flow through orifices to control the flow diverted into interceptors from combined sewers and applied his laboratory findings to a successful full scale project in Portland, Oregon. An interesting aspect to this work was the fact that no vortices of any significance were observed in either tank when the water was allowed to drain naturally with no tangential velocity. Those that did form were small in size, had no effect on the discharge rates, and were quickly dissipated.

Laboratory investigations were conducted by Nelson[4] in 1956 at the University of Minnesota. Using a simple vertical inlet pipe, observations were made on the effect of surface tension on vortex formation. By the addition of a detergent the surface tension of the water was reduced and Nelson observed vortices formed more readily in liquids with decreased surface tension.

In 1957, Plesset[5], at the California Institute of Technology, was awarded a contract by Convair, A Division of General Dynamics

Corporation, to study vortex formation in rotating liquids. However, to date no publication on his findings has been made.

All previous work on vortex formation in liquids has been conducted with the liquids flowing freely from tanks by gravity; therefore, a program was proposed to conduct investigations on the subject while water was being pumped from a tank at different rates. Due to the complexity of the problem and the fact that a study of this type must be limited to investigation of individual factors, this study was conducted with the following questions in mind: what conditions are most conducive to vortex formation, what will be their effect on discharge rates, and can preventative measures be taken to reduce or minimize these effects? The following sections are devoted to a discussion of how these studies were performed and the results obtained from them.

CHAPTER II

EQUIPMENT AND INSTRUMENTATION

The apparatus used in this experiment consisted of the following components: a vertically mounted plastic tank; a rotary pump; five sections of glass piping connecting the discharge of the plastic tank with the pump suction port; sufficient metering devices to permit measurement of the tank discharge rate, and a method of imparting a tangential velocity to the water in the plastic tank in order to vary the intensity of the vortices formed.

A photograph of the equipment is shown in Fig. 1 and a schematic diagram is shown in Fig. 2. The following paragraphs contain a more detailed description of the individual components of the apparatus.

The vertical tank was constructed of two sections of plastic tubing 52 inches long with an outside diameter of 12 inches and a wall thickness of 1/4 inch. The two sections were fastened together with flanges made of 1/2 inch boiler plate and 3/8 inch tie-rods. Gaskets of 1/16 inch rubber were placed between all connecting surfaces to eliminate leaks. The connected sections were mounted in an angle iron frame and supported to allow installation and removal of the tank bottom. The tank was fitted with bottoms of various shapes. Bottom I was a flat circular plate 14 inches in diameter. A 1-1/2 inch pipe coupling was brazed to the geometric center of the plate. Bottom II was a cone made of sheet metal and brazed to a metal flange 14 inches in diameter. The cone was 11-1/2 inches in diameter at the top and 1-1/2 inches in

Figure 1. Experimental Apparatus

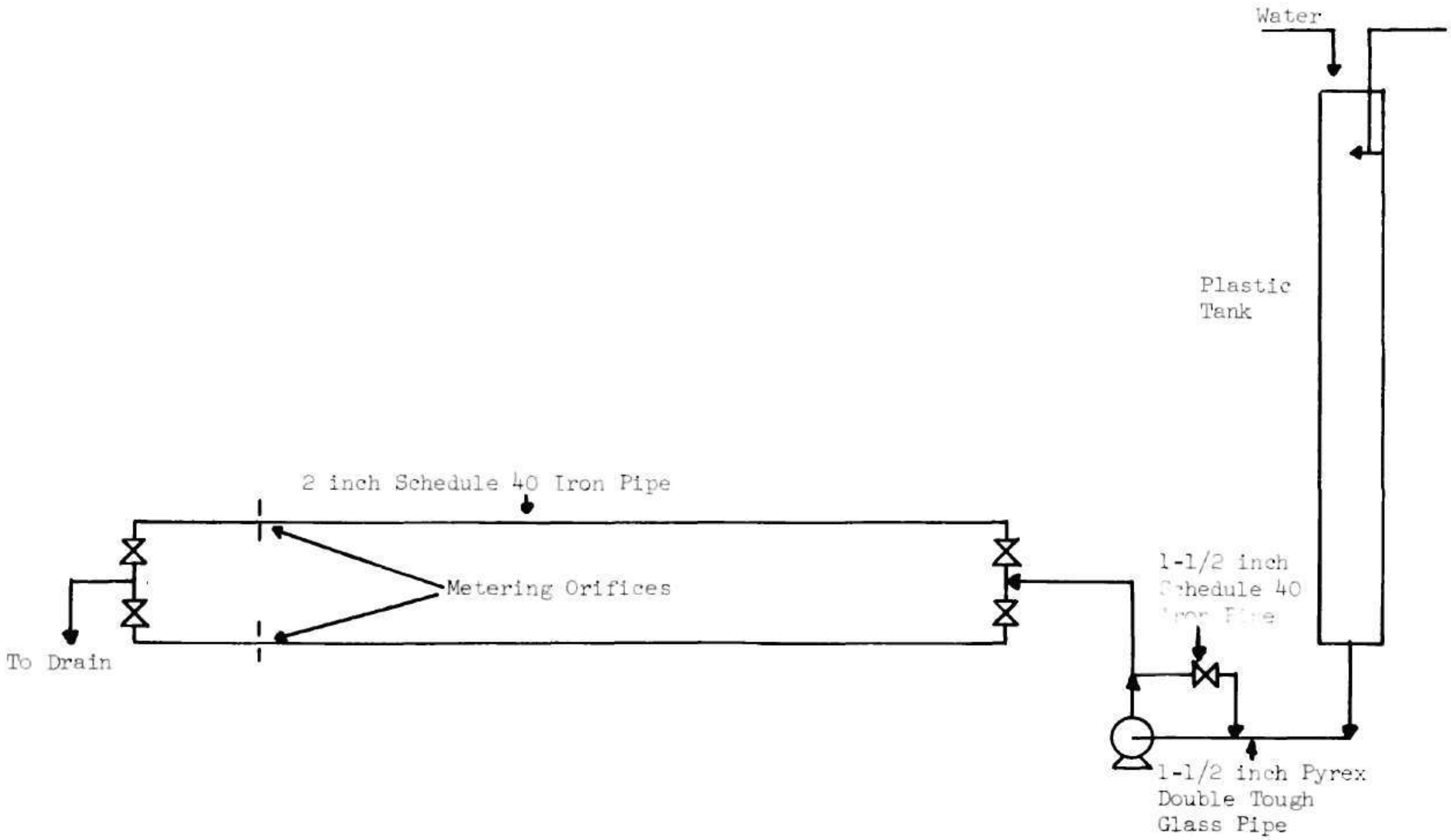

Figure 2. Schematic Diagram of Experimental Apparatus

diameter at the bottom with a slant height of 9 inches. A 1-1/2 inch pipe nipple was brazed to the bottom opening. Bottom III was a flanged and dished head purchased from a local boiler shop made of 3/16 inch steel with an outside diameter of 12 inches. The total depth of the head was 3 inches and the flanged section had a depth of 1-1/2 inches. A 1-1/2 inch nipple was brazed to the bottom opening. Bottom IV was the same flat plate described as Bottom I with a nine inch baffle. The baffle was a flat circular plate 9 inches in diameter, 1/8 inch thick and positioned 1 inch above the geometric center of the flat plate. Bottom V was the same as Bottom IV with the exception that the baffle was 3 inches in diameter instead of 9 inches.

The pump used was a Viking positive displacement rotary pump with a capacity of 90 GPM against a pressure of 35 psi. Since the pump had a positive displacement, a by-pass line with a throttle valve was installed connecting the suction and discharge lines of the pump in order to vary the discharge rate from the plastic tank. A suction gage calibrated in inches of mercury vacuum was installed on the suction side of the pump and a pressure gage calibrated in pounds per square inch was installed on the discharge side of the pump.

The line connecting the plastic tank discharge with the pump suction port was made of 1-1/2 double-tough pyrex glass pipe. The pyrex pipe was connected to the tank bottom by a 4 inch section of 1-1/2 inch rubber hose to minimize the possibility of glass breakage through pump vibration or installation strain. The rubber hose was rigid enough to insure no flow disturbance in that section.

The pump discharge lines consisted of two parallel 2 inch lines with orifice plates installed 40 pipe diameters downstream from the nearest flow disturbance. One orifice had a diameter of 0.718 inches and was used to meter flow from 10 through 30 GPM. The second orifice plate had a diameter of 1.20 inches and was used to meter flows from 40 through 90 GPM. The taps from the two orifice plates were connected by copper tubing and valves to a common U-type mercury manometer.

A mercury thermometer was placed in the discharge line to determine the water temperature.

Water was supplied tangentially to the side of the plastic tank through a section of 3/8 inch copper tubing, which was shaped to conform to the inside perimeter of the tank. Water was supplied to the copper tubing by a 1/2 inch line from the main water supply system. The flow to the copper tubing was metered with a rotameter having a maximum capacity of 16 GPM and calibrated in per cent of maximum flow. The 1/2 inch pipe entered the tank through the top and a union was installed at this point in order to suspend the copper tubing at different heights in the tank.

CHAPTER III

EXPERIMENTAL PROCEDURE

The first phase of the experimental program consisted of calibrating the orifice meters and checking the calibration of the rotameter. This was accomplished by setting the various flow rates and measuring the time to collect a specified weight of water. The water temperature was measured and calibration charts were constructed for the two orifice meters. The previous rotameter calibration proved satisfactory.

The next phase of the experimental program was the performance of the test runs. Runs were made at tank liquid levels of 7 feet 8 inches, 5 feet 9 inches, and 3 feet 10 inches. Since the inside diameter of the tank was 11-1/2 inches, these heights corresponded to height to diameter ratios of 8, 6, and 4 to 1. At a given height measurements were made at eight different tank discharge rates varying from 20 to 90 GPM at 10 GPM increments. At each discharge rate, water was introduced tangentially through the copper tubing at a number of different rates (usually six) varying from 1.6 to 8.0 GPM.

The above described runs were made with bottoms I, II, III, and IV. Runs with bottom V were made at a height to diameter ratio of 4 to 1 only.

The operating procedure was essentially the same for all the test runs. For a typical test run with a given bottom shape, the copper tubing was installed 3 inches below the desired tank liquid level, the tank discharge rate set at 20 GPM, and the tank filled through a supply line to a height 1 inch below the copper tubing. A water rate was set on the rotameter supplying the copper tubing and the tank allowed to fill to the starting height while a tangential velocity component was introduced to the water in the tank. When the desired liquid level was reached, the supply to the copper tubing was shut off, the pump started, and the following measurements made and recorded: the height at which the vortex formed, as indicated by the appearance of a thin line of air bubbles extending downward from the liquid surface to the tank bottom, the pump suction pressure at the time of the vortex formation, the height of the tank liquid when the vortex reached the pump suction port, the pump suction pressure at the time the vortex reached the pump, the reduced tank discharge rate caused by the vortex reaching the pump, and the water temperature. In addition, if the vortex reached the pump at a water height greater than 1 foot, the reduced flow was measured and recorded when the tank level reached 1 foot. These measurements were made at different values of Q_C from 1.6 to 8.0 GPM. The discharge rate was then increased to the next value and a new group of data obtained. This procedure was repeated until the entire range of discharge rates had been covered. The copper tubing was then adjusted to a new height and the above procedure repated until groups of data had been obtained for all these starting heights. The bottom was then removed from the tank, a different one installed, and the above procedure repeated.

The total tank height was increased 8 inches by the conical bottom and 3 inches for the dished bottom over the height with the flat bottom installed. However, these increases were not included in making tank height measurements and all such measurements presented in the data are based on a common datum plane, i.e., the bottom of the tank plastic.

The complete experimental data obtained are presented in Tables 1, 2, and 3.

CHAPTER IV

DIMENSIONAL ANALYSIS

Consideration of the physical situation concerning the height of vortex formation in a cylindrical tank indicates the following factors are involved: the tank diameter, the discharge pipe diameter, the liquid viscosity, the liquid density, the initial water height, the tank discharge rate, the torque applied, which in this case is equal to the momentum of the liquid leaving the copper tubing times the tank radius, and the length of time the torque was applied. Therefore,

$$h_f = \phi_1 \,(D,\ d,\ \mu,\ \rho,\ h_o,\ g,\ q,\ P,\ T,\ t) \qquad (1)$$

Using the $ML\theta$ system, it was determined by trial and error that the largest number of these variables which could be combined without forming a dimensionless group was three. Therefore, by the π theorem, since there are eleven variables, there are eleven minus three or eight dimensionless groups. Since D, μ, and ρ do not form a dimensionless group, the eight dimensionless groups can be formulated as

$$\pi_1 = \frac{h_f}{D^{a1}\ \mu^{b1}\ \rho^{c1}} \qquad (2)$$

$$\pi_2 = \frac{d}{D^{a2}\ \mu^{b2}\ \rho^{c2}} \qquad (3)$$

$$\pi_3 = \frac{h_o}{D^{a3}\ \mu^{b3}\ \rho^{c3}} \qquad (4)$$

$$\pi_4 = \frac{g}{D^{a4}\ \mu^{b4}\ \rho^{c4}} \tag{5}$$

$$\pi_5 = \frac{P}{D^{a5}\ \mu^{b5}\ \rho^{c5}} \tag{6}$$

$$\pi_6 = \frac{q}{D^{a6}\ \mu^{b6}\ \rho^{c6}} \tag{7}$$

$$\pi_7 = \frac{T}{D^{a7}\ \mu^{b7}\ \rho^{c7}} \tag{8}$$

$$\pi_8 = \frac{t}{D^{a8}\ \mu^{b8}\ \rho^{c8}} \tag{9}$$

Solving for the primary quantities, M, L, and θ, in terms of the variables, D, μ, and ρ, the following expressions are obtained

$$L = D \tag{10}$$

$$M = L^3\rho = D^3\rho \tag{11}$$

$$\theta = \frac{M}{L\mu} = \frac{D^2\rho}{\mu} \tag{12}$$

Replacing the primary quantities in the above formulated groups, the following dimensionless groups are obtained.

$$\pi_1 = \frac{h_f}{D} \tag{13}$$

$$\pi_2 = \frac{d}{D} \tag{14}$$

$$\pi_3 = \frac{h_o}{D} \tag{15}$$

$$\pi_4 = \frac{g\ D^3\ \rho^2}{\mu^2} \tag{16}$$

$$\pi_5 = \frac{P\ \rho\ D^2}{\mu^2} \tag{17}$$

$$\pi_6 = \frac{D\mu}{\rho q} \tag{18}$$

$$\pi_7 = \frac{T\rho}{D\mu^2} \tag{19}$$

$$\pi_8 = \frac{t\mu}{\rho D^2} \tag{20}$$

Eq. 1 can now be written as,

$$\frac{h_f}{D} = \phi_2\ \left(\frac{h_o}{D}\right)\ \left(\frac{d}{D}\right)\ \left(\frac{g\ \rho^2\ D^3}{\mu^2}\right)\ \left(\frac{D\mu}{\rho q}\right)\ \left(\frac{P\ \rho\ D^2}{\mu^2}\right)\left(\frac{T\rho}{D\mu^2}\right)\ \left(\frac{t\mu}{\rho D^2}\right) \tag{21}$$

For purposes of this investigation, the following changes were made. Squaring π_8 and multiplying by π_7 resulted in a quantity that, in this particular study, was constant. Therefore, one of these two groups can be discarded and Eq. 21 becomes,

$$\frac{h_f}{D} = \phi_3\ \left(\frac{h_o}{D}\right)\ \left(\frac{d}{D}\right)\ \left(\frac{g\ \rho^2\ D^3}{\mu^2}\right)\ \left(\frac{D\mu}{\rho q}\right)\ \left(\frac{P\ \rho\ D^2}{\mu^2}\right)\ \left(\frac{T\rho}{D\mu^2}\right) \tag{22}$$

The last two terms of the above equation can be combined to form a group that depends both on torque and flow rate. Performing this manipulation, Eq. 22 becomes

$$\frac{h_f}{D} = \phi_4 \left(\frac{h_o}{D}\right) \left(\frac{d}{D}\right) \left(\frac{g \rho^2 D^3}{\mu^2}\right) \left(\frac{P \rho D^2}{\mu^2}\right) \left(\frac{D\mu}{\rho q}\right) \left(\frac{T}{q\mu}\right) \qquad (23)$$

The above equation will be used to correlate the data obtained in this investigation.

CHAPTER V

DISCUSSION OF RESULTS

The data and calculated results are presented in Tables 1, 2, and 3 and in Figs. 8 through 17. Figs. 3 through 7 present a photographic study of vortex formation and growth.

The data obtained in the investigation were reproducible within the experimental error. The experimental error incurred in making height measurements was approximately 1 inch on runs with discharge rates of 20 to 50 GPM and 2 inches on runs with rates of 60 to 90 GPM. The percentage of error in height measurements is naturally dependent upon the magnitude of the measurement being made and the readings taken at low heights are highly sensitive to small errors. The accuracy on the pump suction pressure reading is approximately one pound per square inch. The uncertainty in these measurements is caused by the vibration the pump transmitted to the pressure gage.

One of the most interesting aspects of this study was the visual observation of the vortices formed; therefore, a portion of this section will be devoted to a description of these visual observations.

Vortices form in the following sequence. A slight depression develops in the liquid surface, as the rotating liquid moves downward in the tank. This is followed by the formation of a thin stream of entrained air bubbles directly beneath the liquid surface which moves toward the tank bottom. A vortex at this stage of development is shown in Fig. 4. The stream of air bubbles is immediately followed by an

Figure 3. Tank Discharging with no Vortex

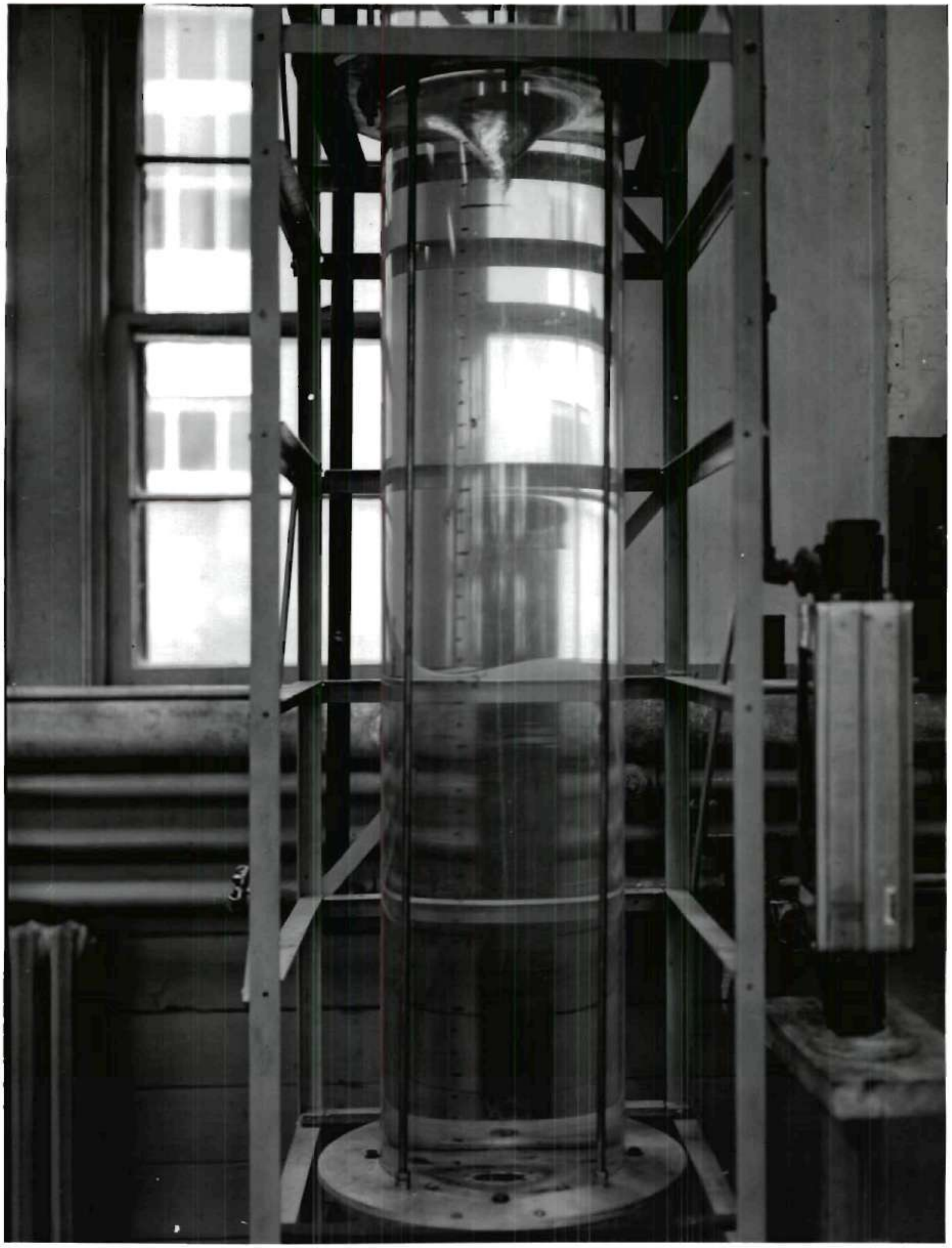

Figure 4. A Vortex in an Early Stage of Development

Figure 5. A Vortex in an Intermediate Stage of Development

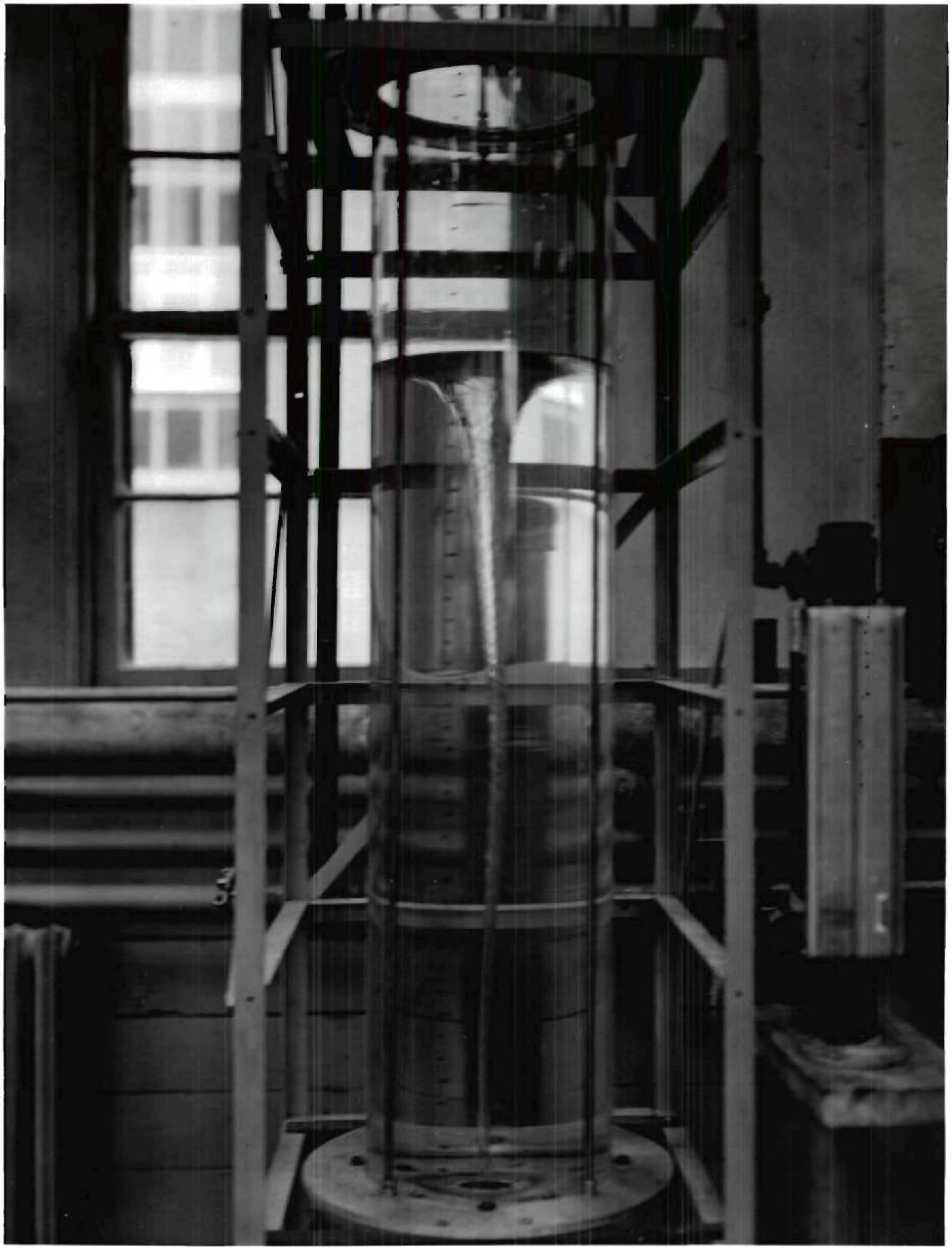

Figure 6. A Fully Developed Vortex

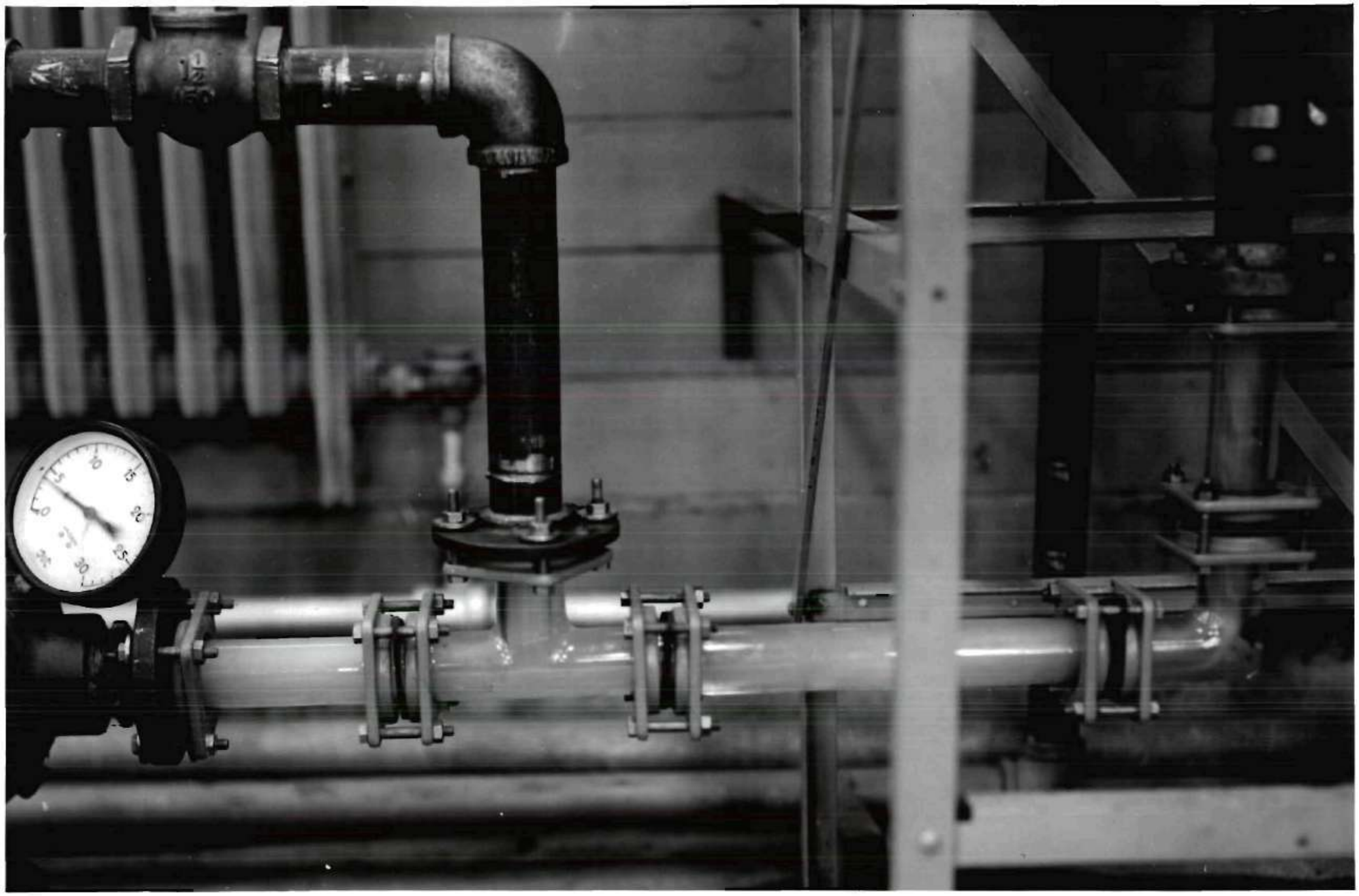

Figure 7. Effect of Vortex on Pump Suction Conditions

inverted cone of air, which develops in the liquid surface and moves downward into the liquid in the tank. This stage is presented in Fig. 5. The cone of air continues downward to the tank bottom and into the pump suction line. The vortex is now fully developed and is presented in Fig. 6. The vortex enters the pump suction line and finally reaches the pump suction port. The flow in the pump suction line is two-phase fluid flow and varies from annular flow, in which the air stream causes the liquid to assume an annular flow channel against the pipe wall, to slug flow, in which slugs of liquid move through the pipe with the air stream controlling. The effect of a vortex on pump suction conditions is shown in Fig. 7.

The rapidity at which these vortices develop is directly proportional to the tank discharge rate, i.e., the higher the rate the more rapid the growth.

The data in Table 1 were correlated by a series of graphs using the relations derived in Chapter IV. The pressure in the discharge line was experimentally determined to be a function of the height of liquid in the tank only and did not depend upon the presence of a vortex, the rate of liquid rotation, or the rate of discharge. Therefore, the dimensionless group $(\frac{P \rho D^2}{\mu^2})$ was not a variable in this study. The acceleration due to gravity was constant and the water density varied only 0.1 per cent. The water viscosity varied 10 per cent during all runs but only varied 2 per cent during runs made at any one height and bottom shape. Thus, the quantity $(\frac{g \rho^2 D^3}{\mu^2})$ was practically constant. By graphical analysis, the dimensionless group $(\frac{D\mu}{\rho q})$ was eliminated from Eq. 23. This was accomplished by plotting $(\frac{h_f}{D})$ versus $(\frac{T}{q\mu})$ using $(\frac{D\mu}{\rho q})$

as a parameter. All curves obtained from this operation were identical with minor variations. These variations were well within the experimental error; consequently, this parameter was not a variable. Since the tank discharge pipe diameter was held constant Eq. 23 becomes,

$$\frac{h_f}{D} = \phi \left(\frac{h_o}{D}\right) \left(\frac{T}{\mu q}\right) \tag{24}$$

The above equation is considered valid but is only significant for the range of flow rates covered in a tank of the same dimensions as the one used in the performance of this experiment. The graphical representation of Eq. 24 is presented in Figs. 8 through 16. With the aid of these graphs it is possible to determine the effect on vortex formation of each of the variables considered in this investigation.

Effect of Torque.--Approximately 100 runs were made with the tank under quiescent conditions, i.e., with no torque applied to the tank liquid. No vortex was observed in any of these runs. The remaining runs were made with torque applied and the height of vortex formation was found to be directly proportional to the torque, i.e., the height of formation increased as the torque increased, everything else being constant.

Effect of Tank Discharge Rate.--The height of vortex formation decreased as the discharge rate increased, everything else being constant. However, vortices developed more rapidly and had a more pronounced effect on reducing the discharge rate at higher flow rates. Therefore, vortex formation poses a grave problem when considered in systems with high tank discharge rates.

Effect of Initial Water Height.--Both the absolute value of the height of formation and the difference between the initial water height and the height of formation decreased with decreasing initial water heights. This can be explained as follows. The tank contained less liquid at lower initial water heights and consequently offered less resistance to rotational flow. The torque for any given value of Q_c was constant; therefore, at lower initial water heights, a larger percentage of the water in the tank was rotating when the run was started and vortices formed more readily.

Effect of Bottom Shape.--Very little variation was noted in vortex formation with the tank fitted with the three bottom shapes considered in this study. Vortices formed at greater heights in a tank fitted with a flat-shaped bottom than in a tank fitted with a conical-shaped bottom. The dished bottom resulted in heights intermediate to the other two. At low discharge rates, this formation height differential was more pronounced than at high discharge rates, but all such variations were small.

Effect of Baffles.--Baffles were placed in the tank with a flat bottom in order to attempt to reduce the possibility of vortex formation and its undesirable effect on discharge rates. The first baffle used was a 9 inch circular plate located over the geometric center and one inch above the tank bottom. All runs made without the baffle were repeated with the baffle present and no vortices were observed in any of these runs. The second baffle used was a circular plate three inches in diameter and located precisely as the first. This smaller baffle had a diameter equal to twice the diameter of the tank discharge pipe and was used in order to determine the minimum baffle size required to reduce vortex formation. Runs were made with this baffle at an initial water height to diameter ratio of 4 to 1 and no vortices were observed.

Effect on Discharge Rates.--The reduction in discharge rate due to vortex formation varied over a wide range. These reduced rates were difficult to measure since the resulting slug flow caused large fluctuations in the mercury manometer readings. Attempts were made to obtain sufficient data to represent the reduced discharge rate as a function of the tank water height. However, the vertical velocity in the tank was too high to permit a satisfactory number of readings to be taken. Fig. 17 shows the reduced discharge rate read when the vortex reached the pump as a function of the original discharge rates. The reduced values represent an average of all readings taken at each original rate.

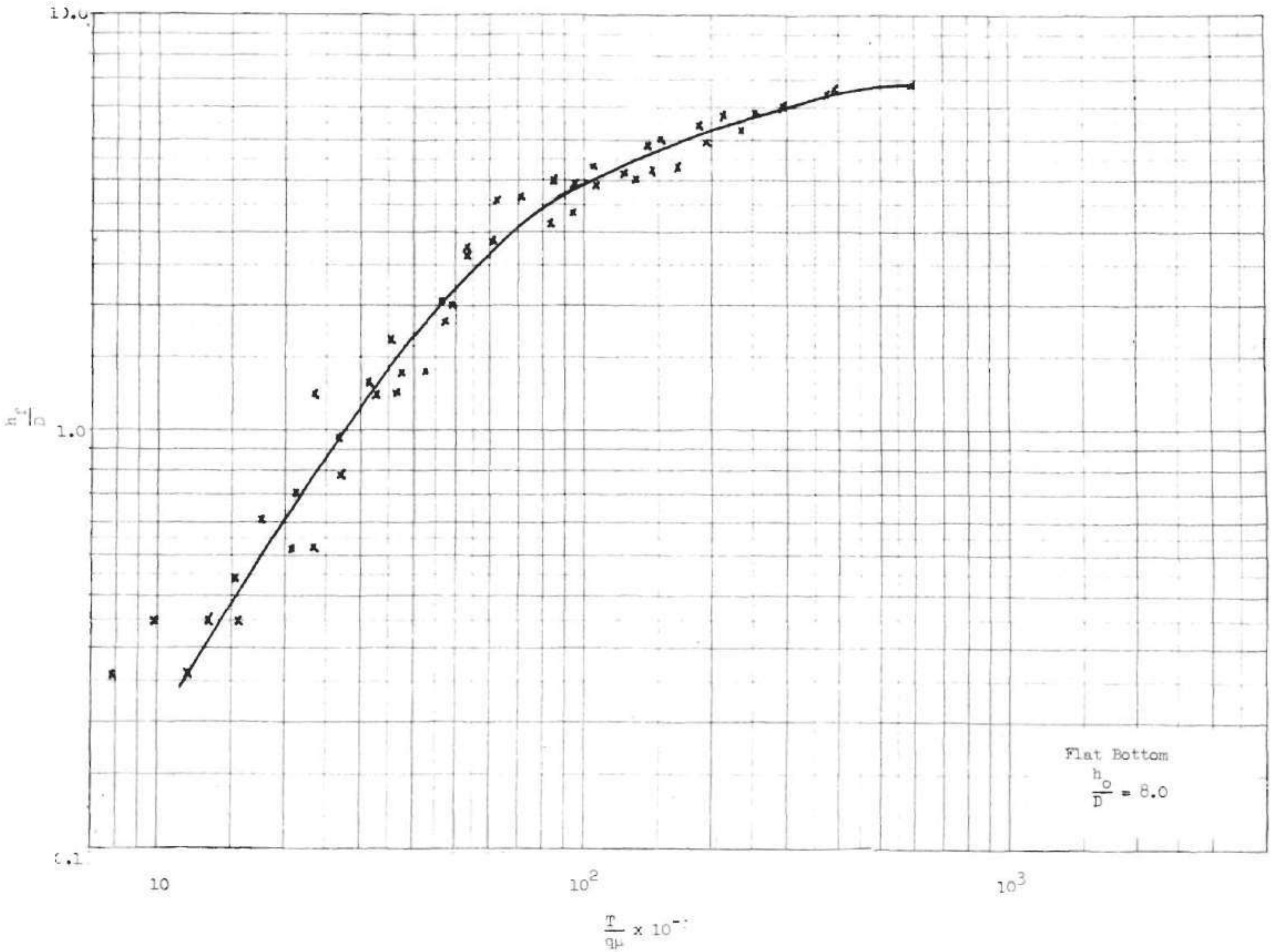

Figure 8

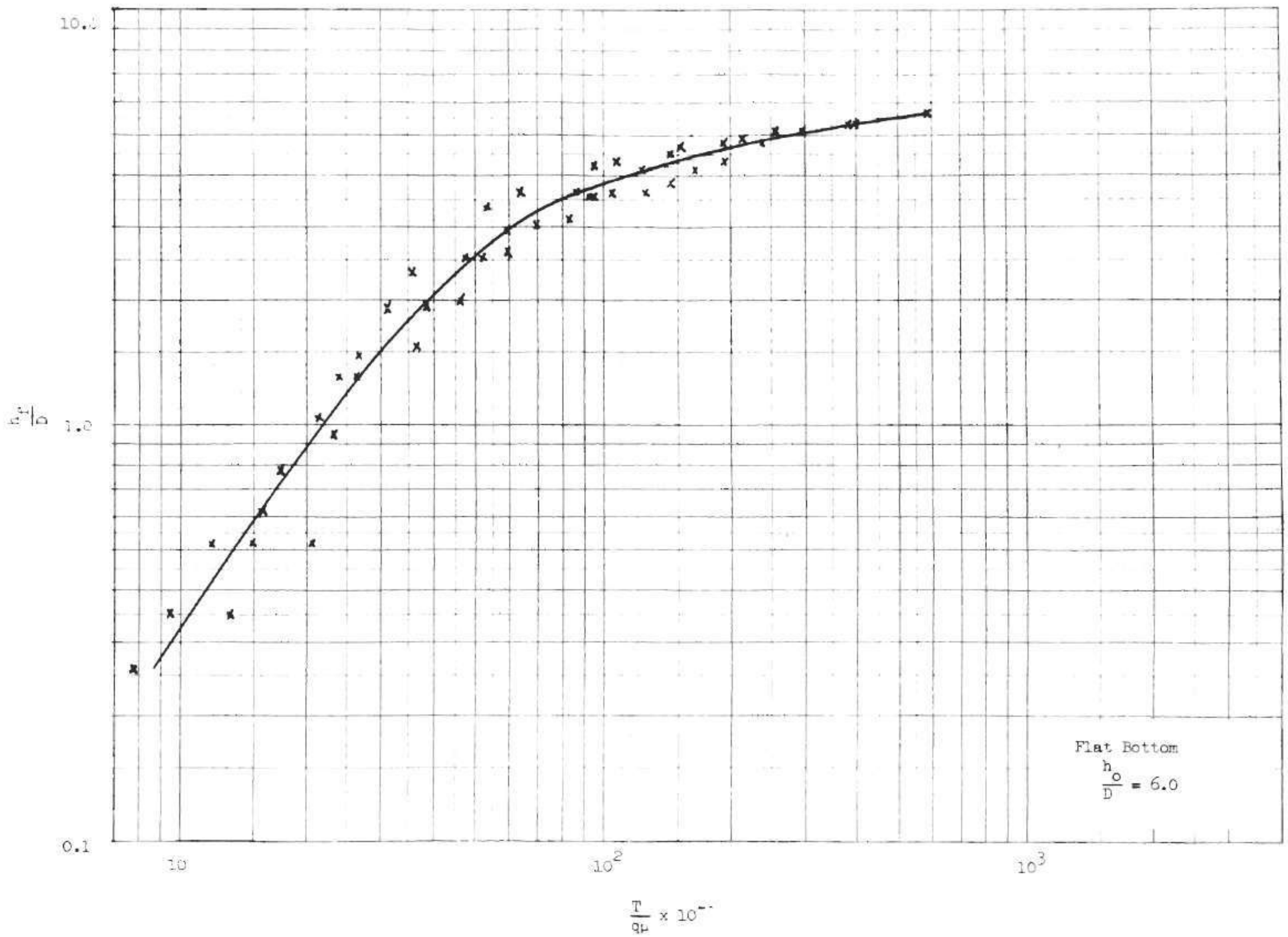

Figure 9

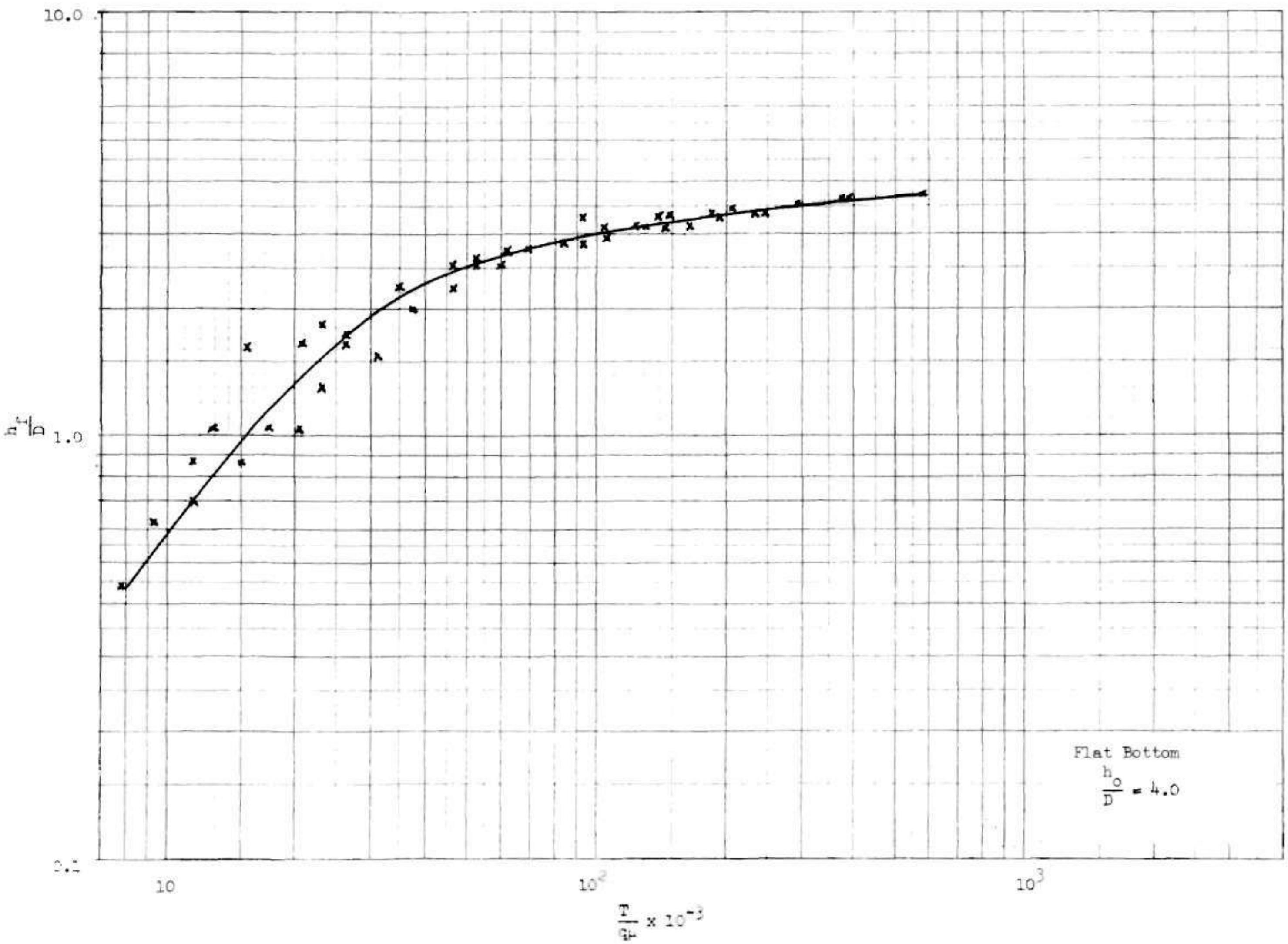
10.0
1.0
0.1
$\frac{h_f}{D}$
10
10^2
10^3
$\frac{T}{q_F} \times 10^{-3}$
Flat Bottom
$\frac{h_o}{D} = 4.0$

Figure 10

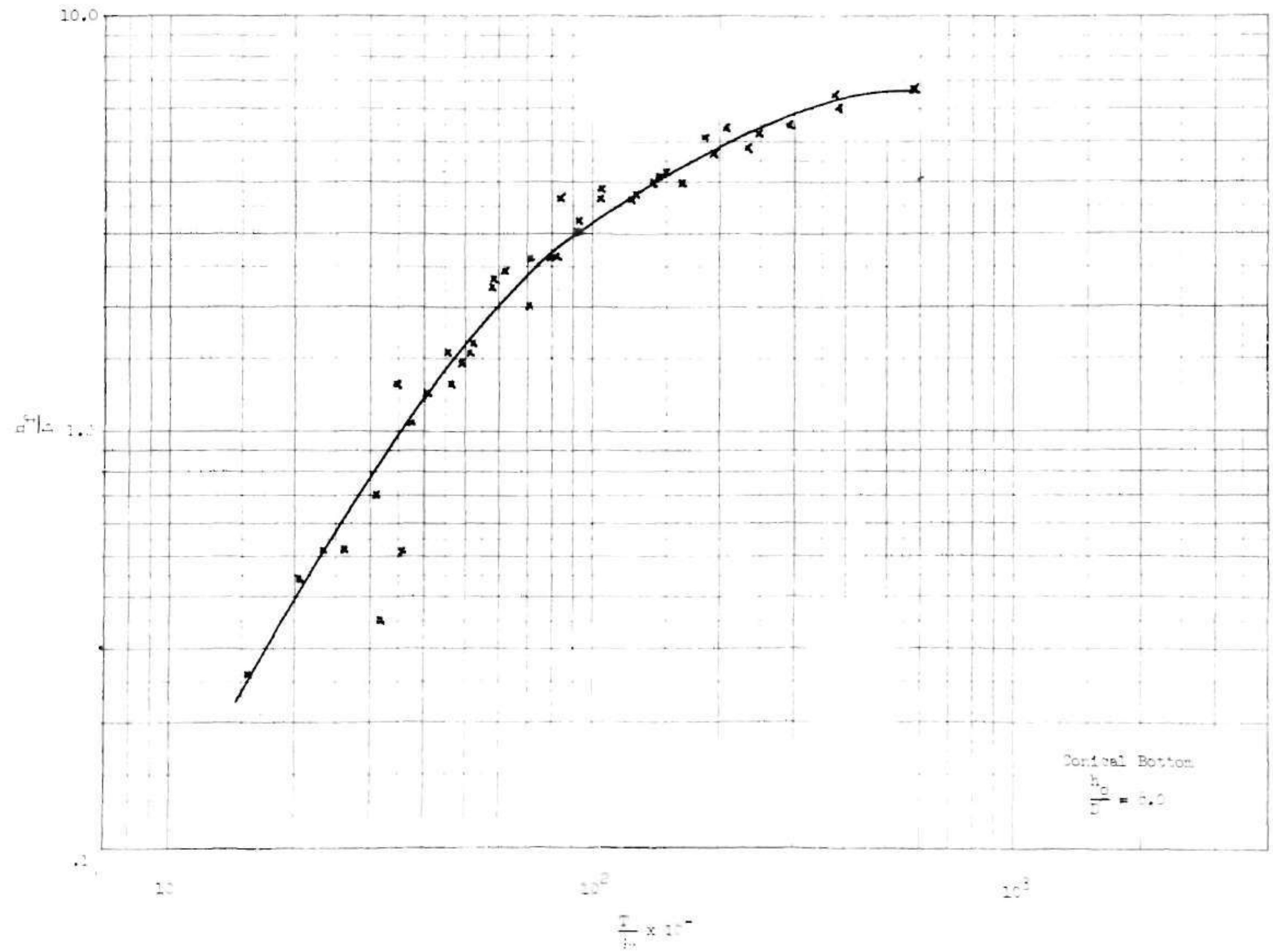

Figure 11

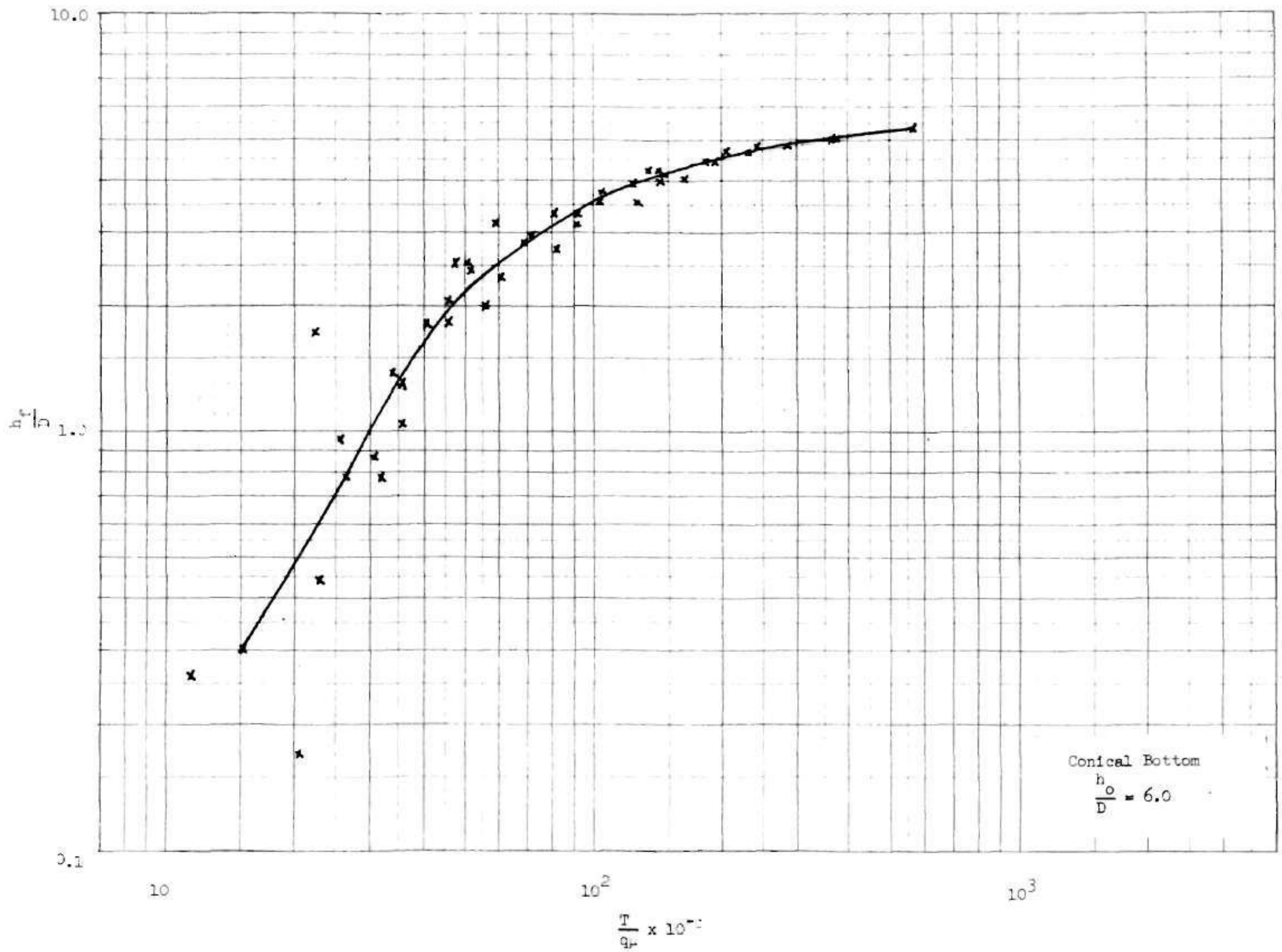
10.0
$\frac{h_t}{D}$
0.1
10
10^2
10^3
$\frac{T}{q_t}$ x 10
Conical Bottom
$\frac{h_o}{D} = 6.0$

Figure 12

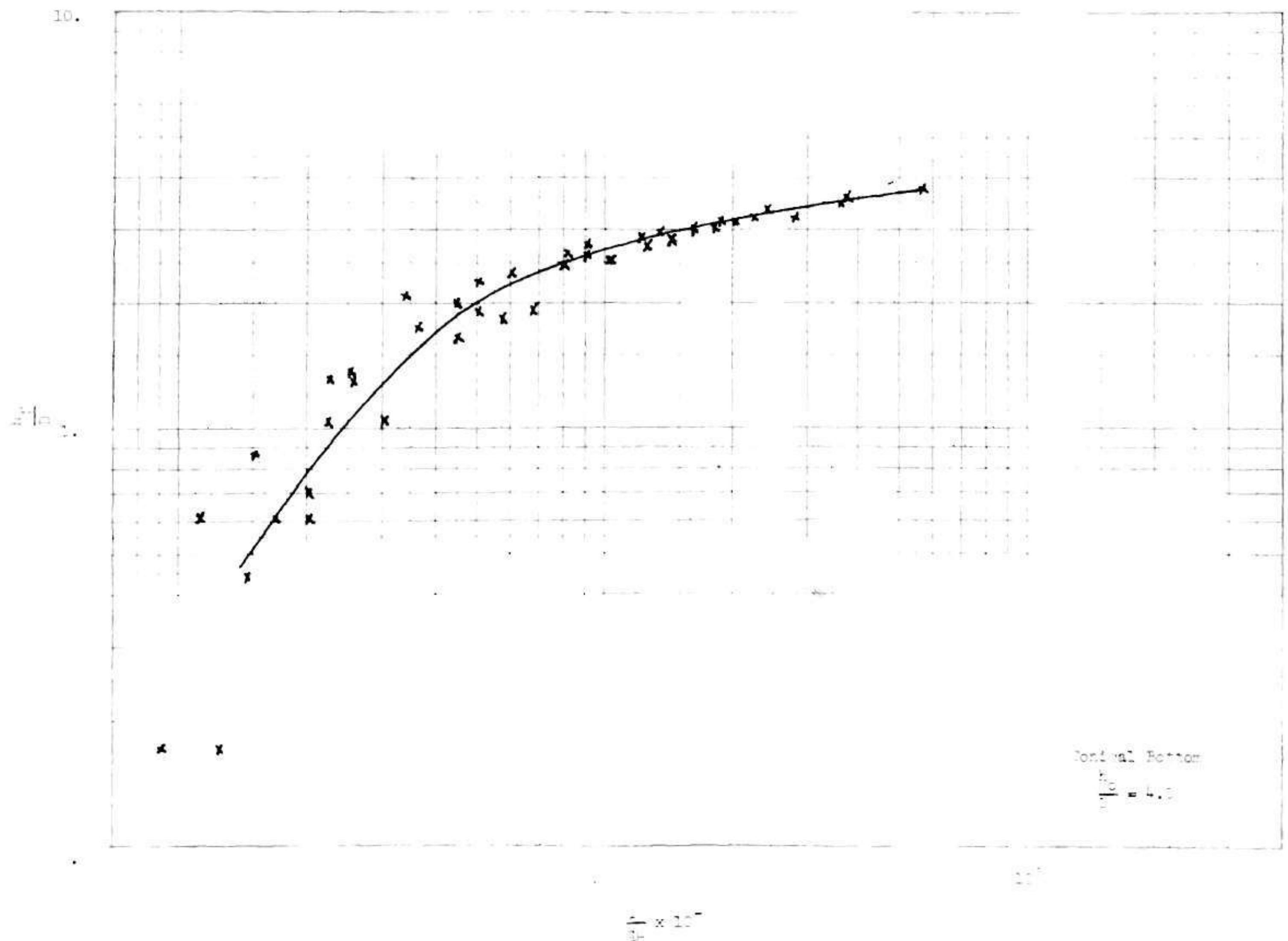

Figure 13

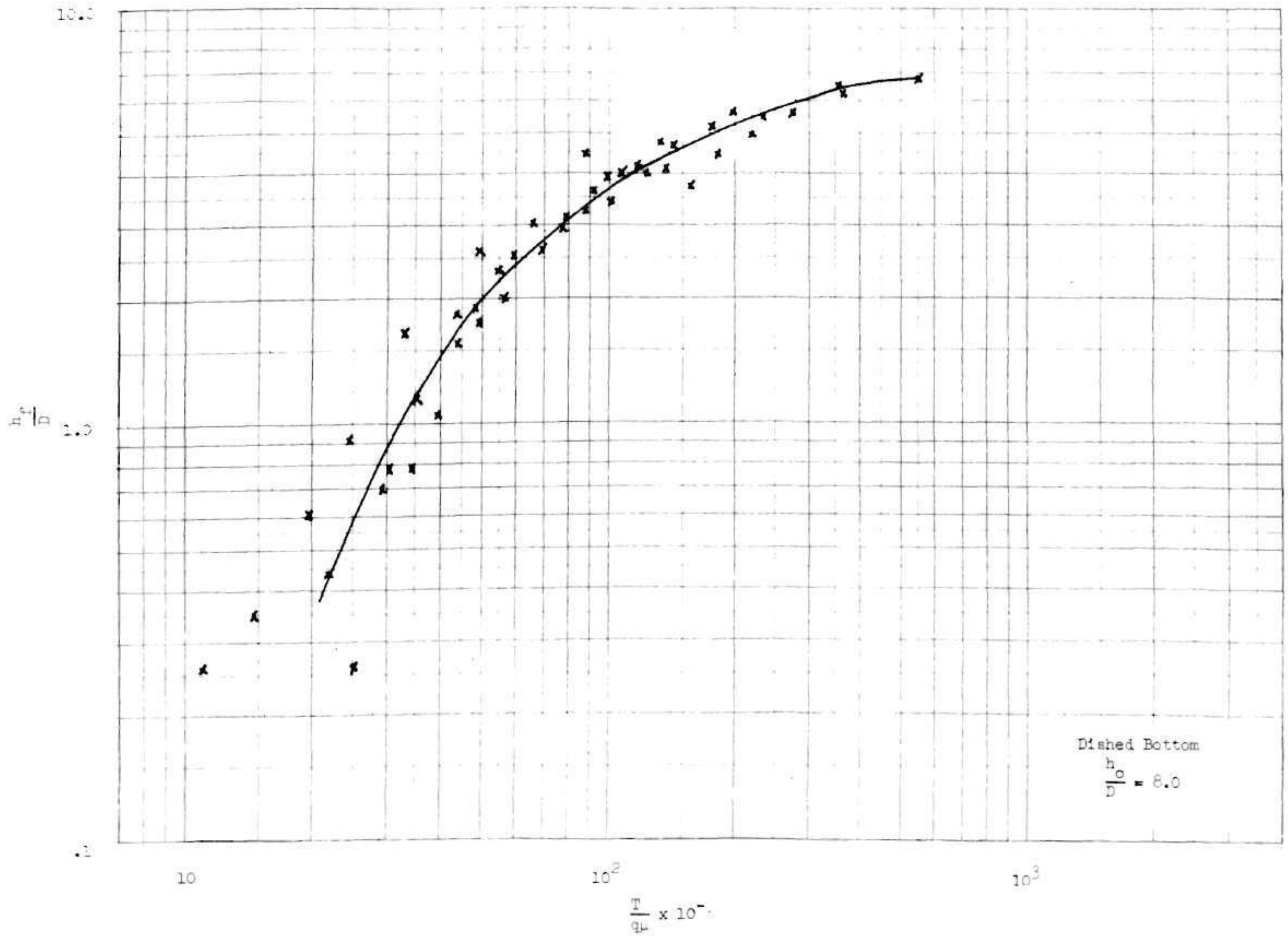

Figure 14

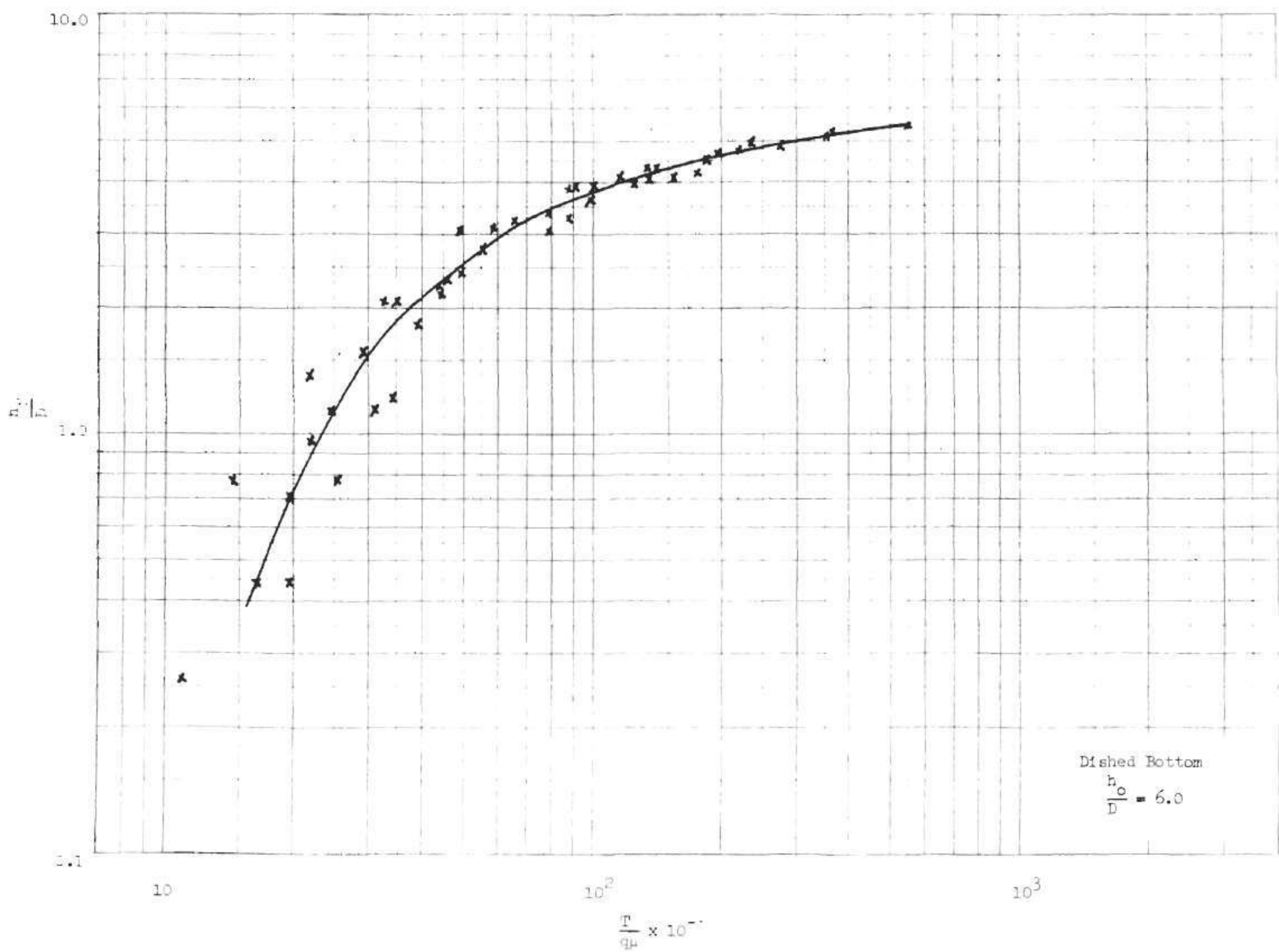

Figure 15

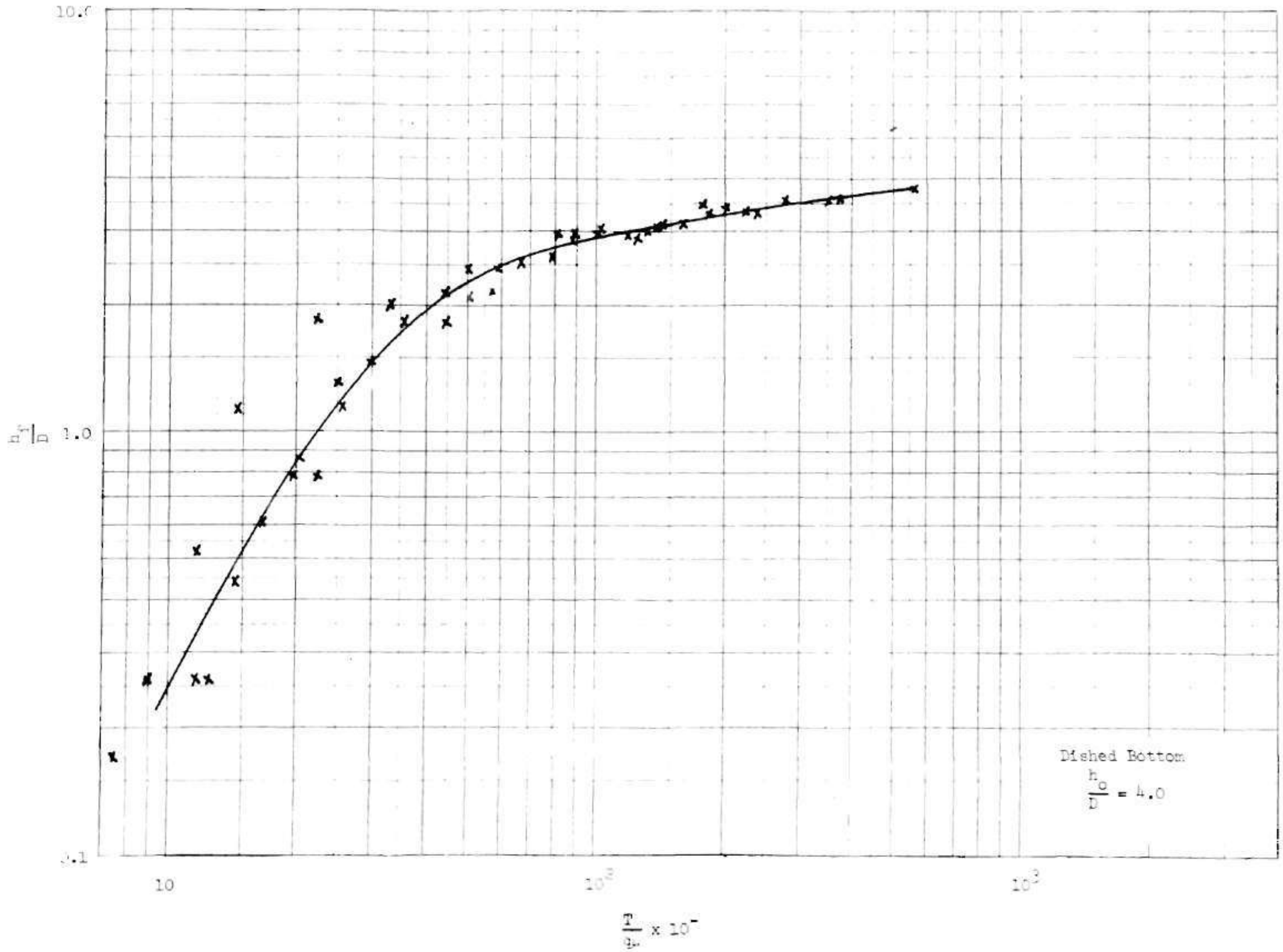

Figure 16

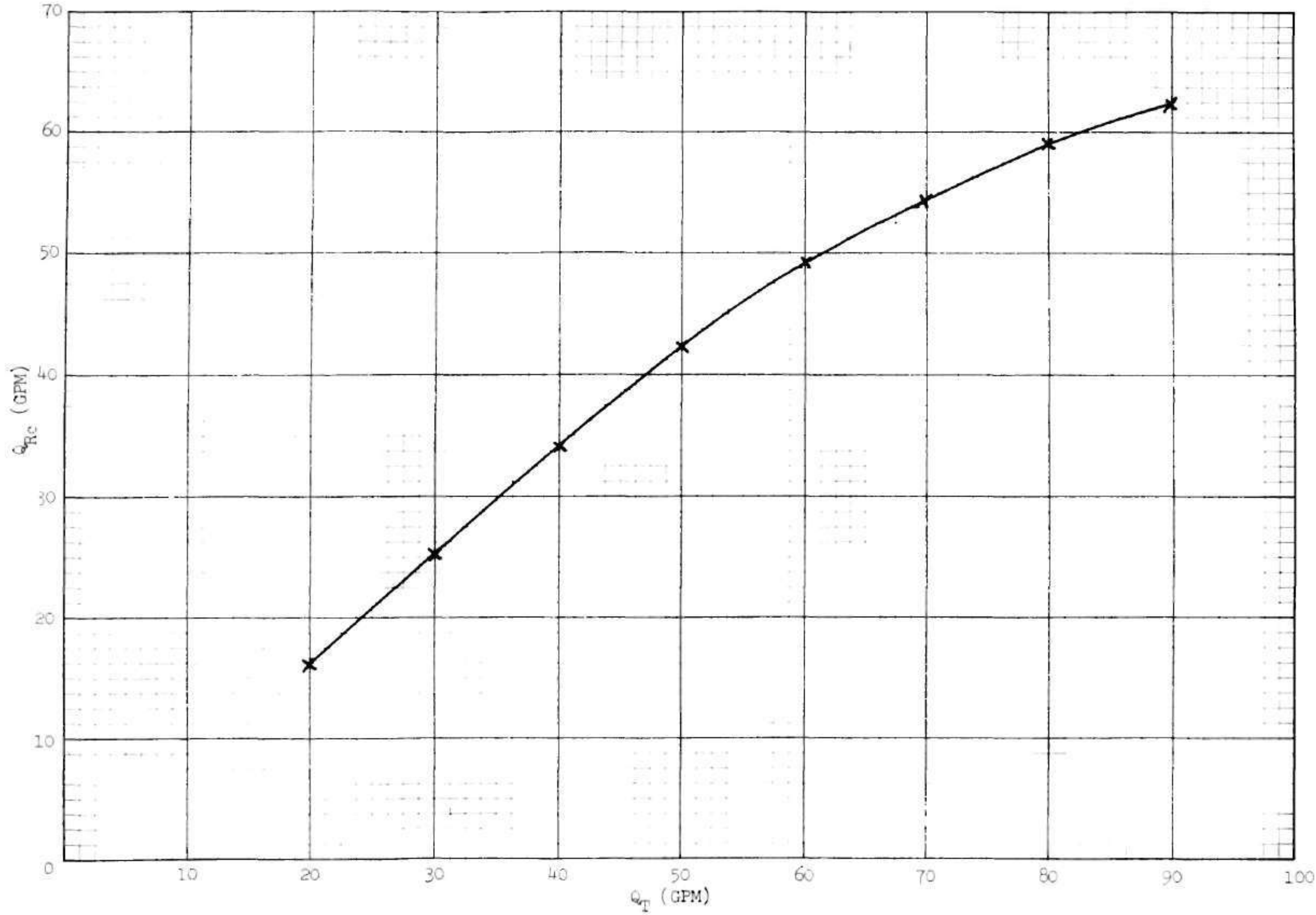

Figure 17

CHAPTER VI

CONCLUSIONS

The conclusions resulting from this investigation are considered valid and significant for a tank of the same dimensions and over a range of flow rates identical with the ones used in this study. They are summarized as follows:

1. The height of vortex formation to tank diameter ratio was found to be a function of two dimensionless groups, the result being

$$\frac{h_f}{D} = \Phi \left(\frac{T}{q\mu}\right) \left(\frac{h_o}{D}\right)$$

2. Once initiated, vortices developed rapidly and reduced pump performance at high flow rates.

3. Vortex formation is not influenced by the shape of the three tank bottoms used in this investigation.

4. Circular baffles can be effectively employed to eliminate vortices in tanks with flat bottoms.

APPENDIX

Table 1A

Data and Results for Tank with Flat Bottom, $\frac{h_o}{D} = 8.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
1	20	0.0	n.v.		n.c.		67	n.a.	n.a.		
2	20	1.6	1.22	12.8	n.c.		67	n.a.	n.a.	23.62	23.60
3	20	2.4	2.78	13.3	n.c.		67	n.a.	n.a.	23.62	53.10
4	20	3.2	3.91	13.3	0.17	11.8	67	15	n.a.	23.62	94.40
5	20	4.8	5.74	13.8	0.17	11.8	67	16	n.a.	23.62	212.40
6	20	6.4	6.44	13.8	0.26	11.8	67	16	n.a.	23.62	377.59
7	20	8.0	6.87	13.8	0.26	11.8	67	17	n.a.	23.62	589.98
8	30	0.0	n.v.		n.c.		67	n.a.	n.a.		
9	30	1.6	0.35	12.6	n.c.		67	n.a.	n.a.	15.75	15.73
10	30	2.4	1.65	12.8	0.26	11.8	67	25	n.a.	15.75	35.40
11	30	3.2	3.57	13.3	0.35	11.8	67	26	n.a.	15.75	62.93
12	30	4.8	4.87	13.3	0.52	11.8	67	26	n.a.	15.75	141.60
13	30	6.4	5.83	13.6	0.61	11.8	67	27	n.a.	15.75	251.70
14	30	8.0	6.61	13.8	0.70	11.8	67	27	n.a.	15.75	293.32
15	40	0.0	n.v.		n.c.		68	n.a.	n.a.		
16	40	1.6	0.26	12.3	n.c.		68	n.a.	n.a.	11.64	11.97
17	40	2.4	0.96	12.3	0.52	11.8	68	30	n.a.	11.64	26.94
18	40	3.2	2.09	12.3	0.70	11.8	67	31	n.a.	11.81	47.20
19	40	4.8	4.35	12.3	1.83	12.3	67	32	32	11.81	106.20
20	40	6.4	5.48	12.8	1.91	12.3	67	33	33	11.81	188.79
21	40	8.0	6.00	12.8	2.00	12.8	67	34	34	11.81	294.99
22	50	0.0	n.v.		n.c.		67	n.a.	n.a.		
23	50	1.6	0.35	11.8	n.c.		67	n.a.	n.a.	9.45	9.44
24	50	2.4	0.70	11.8	0.26	11.8	67	37	n.a.	9.45	21.24
25	50	3.2	1.39	11.8	1.04	11.8	67	37	37	9.45	37.76
26	50	4.8	4.00	12.3	1.83	12.3	67	42	37	9.45	84.96
27	50	6.4	5.04	12.3	2.44	12.3	67	46	32	9.45	151.04

Table 1A (Continued)

Data and Results for Tank with Flat Bottom, $\frac{h_o}{D} = 8.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
28	50	8.0	5.30	12.8	3.48	12.8	67	46	26	9.45	235.99
29	60	0.0	n.v.		n.c.		67	n.a.	n.a.		
30	60	1.6	0.26	11.8	n.c.		67	n.a.	n.a.	7.87	7.87
31	60	2.4	0.61	11.8	0.26	11.8	67	42	n.a.	7.87	17.70
32	60	3.2	1.30	11.8	0.70	11.8	67	45	n.a.	7.87	31.47
33	60	4.0	2.00	11.8	1.30	11.8	67	42	42	7.87	49.17
34	60	4.8	3.65	12.3	1.65	11.8	67	50	37	7.87	70.80
35	60	6.4	4.17	12.3	2.52	11.8	67	53	32	7.87	125.86
36	60	8.0	4.96	12.3	3.48	11.8	67	53	32	7.87	196.67
37	70	0.0	n.v.	12.3	n.c.		67	n.a.	n.a.		
38	70	1.6	0.26	11.4	0.17	11.4	67	37	n.a.	6.75	6.74
39	70	2.4	0.44	11.4	0.26	11.4	67	47	n.a.	6.75	15.17
40	70	3.2	0.78	11.8	0.44	11.4	67	53	n.a.	6.75	26.97
41	70	4.0	1.39	11.8	0.96	11.4	67	57	n.a.	6.75	42.15
42	70	4.8	2.87	11.8	1.39	11.4	67	60	60	6.75	60.68
43	70	6.4	3.91	11.8	2.17	11.4	67	60	32	6.75	107.88
44	70	8.0	4.35	12.3	2.78	11.8	67	60	32	6.75	168.57
45	80	0.0	n.v.		n.c.		67	n.a.	n.a.		
46	80	1.6	0.26	10.9	0.17	10.9	67	37	n.a.	5.91	5.90
47	80	2.4	0.35	10.9	0.26	10.9	67	47	n.a.	5.91	13.27
48	80	3.2	0.52	10.9	0.35	10.9	67	57	n.a.	5.91	23.60
49	80	4.0	1.22	11.4	0.79	10.9	67	63	n.a.	5.91	36.87
50	80	4.8	2.61	11.4	1.30	10.9	67	63	60	5.91	53.10
51	80	6.4	3.39	11.4	2.09	10.9	67	63	37	5.91	94.40
52	80	8.0	4.26	11.4	2.70	10.9	67	63	32	5.91	147.50
53	90	0.0	n.v.		n.c.		67	n.a.	n.a.		

Table 1A (Concluded)

Date and Results for Tank with Flat Bottom, $\frac{h_o}{D} = 8.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
54	90.	1.6	0.17	10.4	n.c.		67	n.a.	n.a.	5.25	5.24
55	90	3.2	0.52	10.4	0.44	10.4	67	60	n.a.	5.25	20.98
56	90	4.0	1.22	10.4	0.61	10.4	67	63	n.a.	5.25	32.78
57	90	4.8	1.83	10.9	0.96	10.4	67	65	n.a.	5.25	47.20
58	90	6.4	3.13	10.9	1.65	10.4	67	65	37	5.25	83.91
59	90	8.0	4.00	10.9	2.35	10.4	67	72	27	5.25	131.11

Table 1B

Data and Results for Tank with Flat Bottom, $\frac{h_o}{D} = 6.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
60	20	0.0	n.v.		n.c.		68	n.a.	n.a.		
61	20	1.6	1.30	13.4	0.09	11.9	68	15	n.a.	23.28	23.95
62	20	2.4	3.48	13.4	0.17	11.9	68	16	n.a.	23.28	53.88
63	20	3.2	4.26	13.4	0.17	11.9	68	17	n.a.	23.28	95.80
64	20	4.8	4.96	13.4	0.26	11.9	68	17	n.a.	23.28	215.54
65	20	6.4	5.30	13.4	0.35	11.9	68	18	n.a.	23.28	383.18
66	20	8.0	5.65	13.8	0.44	11.9	68	18	n.a.	23.28	598.72
67	30	0.0	n.v.		n.c.		68	n.a.	n.a.		
68	30	1.6	0.61	12.4	0.26	12.4	68	22	n.a.	15.52	15.97
69	30	2.4	2.35	13.4	0.44	12.4	68	23	n.a.	15.52	35.92
70	30	3.2	3.65	13.4	0.70	12.6	68	25	n.a.	15.52	63.86
71	30	4.8	4.52	13.9	0.87	12.9	68	25	n.a.	15.52	143.69
72	30	6.4	5.13	13.9	1.22	12.9	68	27	27	15.52	255.43
73	30	8.0	5.30	13.9	1.30	12.9	68	26	26	15.52	399.14
74	40	0.0	n.v.		n.c.		68	n.a.	n.a.		
75	40	1.6	0.52	12.4	0.35	11.9	68	30	n.a.	11.64	11.97
76	40	2.4	1.48	12.4	0.79	11.9	68	30	n.a.	11.64	26.94
77	40	3.2	2.52	12.9	1.30	11.9	68	34	33	11.64	47.90
78	40	4.8	4.35	13.4	2.00	12.9	68	33	27	11.64	107.77
79	40	6.4	4.87	13.9	2.78	12.9	68	38	26	11.64	191.59
80	40	8.0	5.13	13.9	2.87	12.9	68	35	27	11.64	299.36
81	50	0.0	n.v.		n.c.		68	n.a.	n.a.		
82	50	1.6	0.35	11.9	0.26	11.9	68	40	n.a.	9.45	9.58
83	50	2.4	1.04	12.4	0.70	11.9	68	43	n.a.	9.45	21.55
84	50	3.2	1.91	12.4	1.30	11.9	68	42	40	9.45	38.32
85	50	4.0	2.96	13.4	1.83	12.1	68	44	36	9.45	59.87

Table 1B (Continued)

Data and Results for Tank with Flat Bottom, $\frac{h_o}{D} = 6.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
86	50	4.8	3.65	13.4	2.44	11.9	68	46	31	9.45	86.22
87	50	6.4	4.70	13.4	3.22	12.4	68	46	26	9.45	153.27
88	50	8.0	4.87	13.4	3.57	12.9	68	46	20	9.45	239.49
89	60	0.0	n.v.		n.c.		66	n.a.	n.a.		
90	60	1.6	0.26	11.9	0.17	11.9	66	45	n.a.	7.97	7.77
91	60	2.4	0.78	11.9	0.52	11.9	66	53	n.a.	7.97	17.48
92	60	3.2	1.91	11.9	0.96	11.9	66	57	n.a.	7.97	31.08
93	60	4.8	3.04	12.7	1.74	12.4	66	50	31	7.97	69.93
94	60	5.6	3.57	13.4	2.09	12.4	66	50	30	7.97	95.19
95	60	6.4	4.17	12.9	2.96	12.2	66	50	27	7.97	124.33
96	60	8.0	4.35	13.4	3.04	11.9	66	52	25	7.97	194.27
97	70	0.0	n.v.		n.c.		66	n.a.	n.a.		
98	70	1.6	0.35	11.9	0.26	11.5	66	60	n.a.	6.83	6.66
99	70	2.4	0.52	11.9	0.35	11.0	66	60	n.a.	6.83	14.99
100	70	3.2	1.30	11.9	0.70	11.5	66	60	n.a.	6.83	26.64
101	70	4.8	2.61	11.9	1.39	11.5	66	57	63	6.83	59.94
102	70	6.4	3.65	12.4	2.52	11.5	66	50	25	6.83	106.57
103	70	8.0	4.17	12.4	2.61	11.5	66	53	25	6.83	166.51
104	80	0.0	n.v.		n.c.		66	n.a.	n.a.		
105	80	1.6	0.26	11.9	0.17	11.9	66	45	n.a.	5.98	5.83
106	80	2.4	0.35	11.9	0.26	11.0	66	45	n.a.	5.98	13.11
107	80	3.2	0.96	11.9	0.52	10.5	66	45	n.a.	5.98	23.31
108	80	4.0	1.57	11.5	0.79	11.0	66	50	n.a.	5.98	36.42
109	80	4.8	2.44	11.5	1.30	10.5	66	53	53	5.98	52.45
110	80	6.4	3.57	11.5	2.26	10.5	66	55	30	5.98	93.25
111	80	8.0	3.83	11.5	2.44	10.5	66	60	25	5.98	145.70

Table 1B (Concluded)

Data and Results for Tank with Flat Bottom, $\frac{h_o}{D} = 6.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
112	90	0.0	n.v.		n.c.		66	n.a.	n.a.		
113	90	1.6	0.26	10.9	0.17	10.9	66	60	n.a.	5.31	5.18
114	90	3.2	0.52	10.4	0.44	10.4	66	60	n.a.	5.31	20.72
115	90	4.8	2.00	10.9	1.13	10.9	66	60	60	5.31	46.62
116	90	6.4	3.13	11.4	1.74	10.9	66	65	30	5.31	82.88
117	90	8.0	3.65	11.4	2.44	10.9	66	65	20	5.31	129.51

Table 1C

Data and Results for Tank with Flat Bottom, $\frac{h_o}{D} = 4.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
118	20	0.0	n.v.		n.c.		66	n.a.	n.a.		
119	20	1.6	1.83	12.8	0.17	11.8	66	15	n.a.	23.91	23.31
120	20	2.4	2.52	12.8	0.26	11.8	66	15	n.a.	23.91	52.45
121	20	3.2	3.30	12.8	0.35	11.1	66	14	n.a.	23.91	93.25
122	20	4.8	3.48	12.8	0.52	11.3	66	15	n.a.	23.91	209.80
123	20	6.4	3.65	12.8	0.70	11.8	66	17	n.a.	23.91	372.98
124	20	8.0	3.74	12.8	0.96	11.3	66	17	n.a.	23.91	582.18
125	30	0.0	n.v.		n.c.		66	n.a.	n.a.		
126	30	1.6	1.65	12.8	0.44	11.8	66	24	n.a.	15.94	15.54
127	30	2.4	2.26	13.3	0.52	11.8	66	23	n.a.	15.94	34.97
128	30	3.2	2.78	13.3	0.61	11.3	66	23	n.a.	15.94	62.16
129	30	4.8	3.30	13.3	1.57	12.3	66	27	25	15.94	139.87
130	30	6.4	3.39	13.3	2.00	12.3	66	28	22	15.94	248.63
131	30	8.0	3.65	13.3	2.61	11.8	66	28	21	15.94	388.52
132	40	0.0	n.v.		n.c.		66	n.a.	n.a.		
133	40	1.6	0.87	11.8	0.52	12.3	66	35	n.a.	11.96	11.66
134	40	2.4	1.65	12.3	1.04	11.4	66	35	n.a.	11.96	26.23
135	40	3.2	2.52	12.8	1.57	11.9	66	37	25	11.96	46.62
136	40	4.8	3.13	12.8	2.09	11.4	66	36	22	11.96	104.90
137	40	6.4	3.39	13.3	2.44	11.9	66	37	23	11.96	186.49
138	40	8.0	3.57	13.3	2.78	11.4	66	37	20	11.96	291.39
139	50	0.0	n.v.		n.c.		66	n.a.	n.a.		
140	50	1.6	0.61	11.8	0.44	11.4	66	42	n.a.	9.57	9.32
141	50	2.4	1.65	12.3	1.04	12.3	66	42	42	9.57	20.98
142	50	3.2	2.00	12.3	1.48	11.8	66	42	40	9.57	37.30
143	50	4.8	2.87	12.3	2.26	12.3	66	42	38	9.57	83.92

Table 1C (Continued)

Data and Results for Tank with Flat Bottom, $\frac{h_o}{D} = 4.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
144	50	6.4	3.30	12.8	2.61	11.8	66	44	30	9.57	149.19
145	50	8.0	3.39	12.8	2.70	11.8	66	46	32	9.57	233.11
146	60	0.0	n.v.		n.c.		66	n.a.	n.a.		
147	60	1.6	0.44	11.8	0.35	11.8	66	52	n.a.	7.97	7.77
148	60	2.4	1.04	11.8	0.87	11.8	66	52	n.a.	7.97	17.48
149	60	3.2	1.57	11.4	1.22	11.8	66	52	50	7.97	31.09
150	60	4.8	2.78	12.3	2.09	11.8	66	53	32	7.97	69.93
151	60	6.4	3.13	12.3	2.61	11.4	66	56	20	7.97	124.33
152	60	8.0	3.30	12.3	2.87	11.8	66	55	20	7.97	194.27
153	70	0.0	n.v.		n.c.		66	n.a.	n.a.		
154	70	1.6	0.35	11.4	0.26	11.8	66	40	n.a.	6.83	6.66
155	70	2.4	0.87	11.4	0.70	12.3	66	45	n.a.	6.83	14.99
156	70	3.2	1.74	11.4	1.22	11.8	66	47	47	6.83	26.64
157	70	4.8	2.52	11.8	1.91	11.8	66	50	31	6.83	59.94
158	70	6.4	2.96	11.8	2.35	12.3	66	52	23	6.83	106.57
159	70	8.0	3.13	11.8	2.70	12.3	66	54	24	6.83	166.51
160	80	0.0	n.v.				66	n.a.	n.a.		
161	80	1.6	0.26	12.3	0.26	12.3	66	50	n.a.	5.98	5.83
162	80	2.4	1.04	11.4	0.70	12.3	66	58	n.a.	5.98	13.11
163	80	3.2	1.30	11.4	0.96	12.3	66	60	n.a.	5.98	23.31
164	80	4.8	2.61	11.8	1.74	12.3	66	63	50	5.98	52.45
165	80	6.4	2.87	11.4	2.26	12.3	66	63	29	5.98	93.25
166	80	8.0	3.13	11.4	2.61	12.3	66	63	26	5.98	145.70
167	90	0.0	n.v.				66	n.a.	n.a.		
168	90	1.6	0.26	10.9	0.17	10.9	66	68	n.a.	5.31	5.18
169	90	2.4	0.70	10.9	0.61	10.9	66	67	n.a.	5.31	11.66

Table 1C (Concluded)

Data and Results for Tank with Flat Bottom, $\frac{h_o}{D}$ = 4.0, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
170	90	3.2	1.04	10.4	0.87	10.9	66	66	n.a.	5.31	20.72
171	90	4.8	2.26	10.4	1.74	10.9	66	66	60	5.31	46.62
172	90	6.4	2.87	10.9	2.09	11.8	66	68	32	5.31	82.88
173	90	8.0	3.13	9.9	2.44	10.9	66	71	25	5.31	129.51

Table 2A

Data and Results for Tank with Conical Bottom, $\frac{h_o}{D} = 8.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
174	20	0.0	n.v.		n.c.		66	n.a.	n.a.		
175	20	1.6	0.52	1.28	n.c.		66	n.a.	n.a.	23.91	23.31
176	20	2.4	1.65	13.0	n.c.		66	n.a.	n.a.	23.91	52.45
177	20	3.2	3.22	13.3	n.c.		66	n.a.	n.a.	23.91	93.25
178	20	4.8	5.39	13.5	n.c.		66	n.a.	n.a.	23.91	209.80
179	20	6.4	6.26	13.8	n.c.		66	n.a.	n.a.	23.91	372.98
180	20	8.0	6.70	13.8	n.c.		66	n.a.	n.a.	23.91	582.78
181	30	0.0	n.v.		n.c.		66	n.a.	n.a.		
182	30	1.6	0.26	12.3	n.c.		66	n.a.	n.a.	15.94	15.54
183	30	2.4	1.30	12.8	n.c.		66	n.a.	n.a.	15.94	34.97
184	30	3.2	2.44	12.8	n.c.		66	n.a.	n.a.	15.94	62.16
185	30	4.8	4.00	12.8	n.c.		66	n.a.	n.a.	15.94	139.87
186	30	6.4	5.22	12.8	n.c.		66	n.a.	n.a.	15.94	248.63
187	30	8.0	6.00	12.8	n.c.		66	n.a.	n.a.	15.94	388.52
188	40	0.0	n.v.		n.c.		66	n.a.	n.a.		
189	40	1.6	0.09	11.8	n.c.		66	n.a.	n.a.	11.96	11.66
190	40	2.4	0.52	11.8	n.c.		66	n.a.	n.a.	11.96	26.23
191	40	3.2	1.30	12.3	0.17	12.8	66	25	n.a.	11.96	46.62
192	40	4.8	3.83	12.8	0.79	12.3	66	32	n.a.	11.96	104.90
193	40	6.4	5.13	13.3	1.30	12.3	66	27	27	11.96	186.49
194	40	8.0	5.48	13.3	1.39	11.8	66	27	27	11.96	291.39
195	50	0.0	n.v.		n.c.		66	n.a.	n.a.		
196	50	1.6	n.v.		n.c.		66	n.a.	n.a.		
197	50	2.4	0.44	11.8	n.c.		66	n.a.	n.a.	9.57	20.98
198	50	3.2	1.04	12.3	0.26	11.8	66	43	n.a.	9.57	37.30
199	50	4.0	2.35	11.8	0.79	11.8	66	43	n.a.	9.57	58.28

Table 2A (Continued)

Data and Results for Tank with Conical Bottom, $\frac{h_o}{D}$ = 8.0, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
200	50	4.8	3.65	12.3	1.22	11.8	66	43	n.a.	9.57	83.92
201	50	6.4	4.26	12.8	1.39	11.8	66	43	43	9.57	149.19
202	50	8.0	4.87	12.8	2.09	12.3	66	47	27	9.57	233.11
203	60	0.0	n.v.		n.c.		66	n.a.	n.a.		
204	60	1.6	n.v.		n.c.		66	n.a.	n.a.		
205	60	2.4	n.v.		n.c.		66	n.a.	n.a.		
206	60	3.2	0.70	11.4	0.26	11.8	66	56	n.a.	7.97	31.09
207	60	4.0	1.48	11.8	0.79	11.4	67	49	n.a.	8.09	49.17
208	60	4.8	2.61	12.3	1.22	11.8	67	49	49	8.09	70.80
209	60	6.4	3.65	12.3	1.83	11.8	66	53	42	7.97	124.33
210	60	8.0	4.70	12.8	2.61	11.8	66	53	37	7.97	194.27
211	70	0.0	n.v.		n.c.		64	n.a.	n.a.		
212	70	1.6	n.v.		n.c.		64	n.a.	n.a.		
213	70	2.4	n.v.		n.c.		64	n.a.	n.a.		
214	70	3.2	0.09	11.8	n.c.		64	n.a.	n.a.		
215	70	4.0	1.22	11.4	0.44	11.4	64	57	n.a.	7.02	40.50
216	70	4.8	2.26	11.8	0.79	11.4	64	62	n.a.	7.02	58.32
217	70	5.6	2.61	12.3	1.30	11.8	64	57	57	7.02	79.38
218	70	6.4	3.65	12.3	1.83	11.8	64	53	45	7.02	103.68
219	70	8.0	4.00	12.3	2.44	11.8	64	57	32	7.02	161.99
220	80	0.0	n.v.		n.c.		65	n.a.	n.a.		
221	80	1.6	n.v.		n.c.		65	n.a.	n.a.		
222	80	2.4	n.v.		n.c.		65	n.a.	n.a.		
223	80	3.2	0.09	11.8	n.c.		65	n.a.	n.a.	6.07	22.96
224	80	4.0	0.52	11.4	0.17	11.4	65	60	n.a.	6.07	35.88
225	80	4.8	1.57	11.5	0.61	11.4	65	53	n.a.	6.07	51.67

Table 2A (Concluded)

Data and Results for Tank with Conical Bottom, $\frac{h_o}{D} = 8.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
226	80	5.6	2.00	11.8	1.04	11.4	65	62	62	6.07	70.33
227	80	6.4	3.04	12.3	1.57	11.8	65	65	60	6.07	91.86
228	80	8.0	4.17	12.3	2.35	11.8	65	63	32	6.07	143.53
229	90	0.0	n.v.		n.c.		65	n.a.	n.a.		
230	90	1.6	n.v.		n.c.		65	n.a.	n.a.		
231	90	3.2	n.v.		n.c.		65	n.a.	n.a.		
232	90	4.0	0.35	10.9	n.c.		65	n.a.	n.a.	5.39	0.35
233	90	4.8	1.57	11.4	0.61	10.9	65	72	n.a.	5.39	1.57
234	90	6.4	2.61	11.4	1.30	11.4	65	70	70	5.39	2.61
235	90	8.0	3.74	12.3	2.00	11.8	65	75	57	5.39	3.74

Table 2B

Data and Results for Tank with Conical Bottom, $\frac{h_o}{D} = 6.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
236	20	0.0	n.v.		n.c.		64	n.a.	n.a.		
237	20	1.6	1.74	13.3	n.c.		64	n.a.	n.a.	24.58	22.68
238	20	2.4	2.52	13.3	n.c.		64	n.a.	n.a.	24.58	51.03
239	20	3.2	3.13	13.3	n.c.		64	n.a.	n.a.	24.58	90.72
240	20	4.0	4.26	13.3	n.c.		64	n.a.	n.a.	24.58	141.74
241	20	4.8	4.70	13.3	n.c.		64	n.a.	n.a.	24.58	204.11
242	20	6.4	5.04	13.3	n.c.		64	n.a.	n.a.	24.58	362.86
243	20	8.0	5.30	13.3	n.c.		64	n.a.	n.a.	24.58	566.98
244	30	0.0	n.v.		n.c.		64	n.a.	n.a.		
245	30	1.6	0.35	12.8	n.c.		64	n.a.	n.a.	16.39	15.12
246	30	2.4	1.39	12.3	0.09	11.8	64	28	n.a.	16.39	34.02
247	30	3.2	2.35	12.3	0.17	12.3	64	28	n.a.	16.39	60.47
248	30	4.8	4.26	13.3	0.26	12.8	64	26	n.a.	16.39	136.07
249	30	6.4	4.87	13.3	0.35	12.3	64	24	n.a.	16.39	241.89
250	30	8.0	5.04	13.3	0.52	12.3	64	23	n.a.	16.39	377.98
251	40	0.0	n.v.		n.c.		65	n.a.	n.a.		
252	40	1.6	0.26	12.3	0.09	11.8	65	37	n.a.	12.14	11.48
253	40	2.4	0.96	12.3	0.35	11.8	65	37	n.a.	12.14	25.84
254	40	3.2	1.83	12.3	0.52	11.8	65	37	n.a.	12.14	45.93
255	40	4.0	2.93	12.8	0.61	11.8	65	37	n.a.	12.14	71.76
256	40	4.8	3.57	13.3	0.79	11.8	65	37	n.a.	12.14	103.34
257	40	6.4	4.44	13.3	1.13	11.8	65	32	32	12.14	183.72
258	40	8.0	4.87	13.3	1.83	12.3	65	37	32	12.14	287.06
259	50	0.0	n.v.		n.c.		63	n.a.	n.a.		
260	50	1.6	0.09	11.4	n.c.		63	n.a.	n.a.	9.98	8.94
261	50	3.2	1.04	11.8	0.26	11.4	63	39	n.a.	9.98	35.74

Table 2B (Continued)

Data and Results for Tank with Conical Bottom, $\frac{h_o}{D} = 6.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (°F)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
262	50	4.0	2.00	12.3	1.22	11.8	63	42	42	9.98	55.84
263	50	4.8	3.30	12.8	1.65	11.8	63	43	39	9.98	80.42
264	50	6.4	4.17	12.8	2.35	11.8	63	43	35	9.71	146.97
265	50	8.0	4.70	13.3	2.87	12.3	65	42	32	9.71	229.64
266	60	0.0	n.v.		n.c.		65	n.a.	n.a.		
267	60	1.6	n.v.		n.c.		65	n.a.	n.a.		
268	60	3.2	0.87	11.8	0.52	12.3	65	52	n.a.	8.09	30.63
269	60	4.0	2.52	11.8	1.13	12.3	65	52	50	8.09	47.85
270	60	4.8	2.87	12.3	1.65	12.3	65	57	38	8.09	68.89
271	60	6.4	3.91	12.8	2.26	12.8	65	52	35	8.09	122.48
272	60	8.0	4.44	12.8	3.04	12.8	65	50	31	8.09	191.38
273	70	0.0	n.v.		n.c.		65	n.a.	n.a.		
274	70	1.6	n.v.		n.c.		65	n.a.	n.a.		
275	70	3.2	0.78	11.4	0.26	11.8	65	58	n.a.	6.94	26.25
276	70	4.0	1.83	11.8	0.70	12.3	65	60	n.a.	6.94	41.01
277	70	4.8	3.13	11.8	1.57	12.3	65	60	37	6.94	59.05
278	70	6.4	3.74	12.3	1.91	12.8	65	56	37	6.94	104.98
279	70	8.0	4.09	12.8	2.70	12.8	65	59	32	6.94	164.03
280	80	0.0	n.v.		n.c.		65	n.a.	n.a.		
281	80	1.6	n.v.		n.c.		65	n.a.	n.a.		
282	80	3.2	0.44	11.4	0.17	11.4	65	63	n.a.	6.07	22.96
283	80	4.0	1.30	11.4	0.61	11.4	65	60	n.a.	6.07	35.88
284	80	4.8	2.44	11.4	1.04	11.4	65	59	59	6.07	51.67
285	80	6.4	3.30	12.3	2.09	11.8	65	64	36	6.07	91.86
286	80	8.0	4.00	1.28	2.70	12.3	65	62	34	6.07	143.53
287	90	0.0	n.v.		n.c.		65	n.a.	n.a.		

Table 2B (Concluded)

Data and Results for Tank with Conical Bottom, $\frac{h_o}{D}$ = 6.0, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
288	90	1.6	n.v.		n.c.		65	n.a.	n.a.		
289	90	3.2	0.17	10.9	n.c.		65	n.a.	n.a.	5.39	20.41
290	90	4.0	0.78	10.9	0.44	10.9	65	66	n.a.	5.39	31.90
291	90	4.8	2.09	11.4	0.96	11.4	65	66	n.a.	5.39	45.93
292	90	6.4	2.78	11.4	1.57	11.4	65	74	43	5.39	81.65
293	90	8.0	3.57	12.3	2.00	11.8	65	71	37	5.39	127.58

Table 2C

Data and Results for Tank with Conical Bottom, $\frac{h_o}{D} = 4.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (°F)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
294	20	0.0	n.v.		n.c.		64	n.a.	n.a.		
295	20	1.6	1.30	13.1	n.c.		64	n.a.	n.a.	24.58	22.68
296	20	2.4	2.26	13.3	n.c.		64	n.a.	n.a.	24.58	51.03
297	20	3.2	2.78	13.3	n.c.		64	n.a.	n.a.	24.58	90.72
298	20	4.8	3.13	13.3	n.c.		64	n.a.	n.a.	24.58	204.11
299	20	6.4.	3.48	13.3	0.09	11.8	64	15	n.a.	24.58	362.86
300	20	8.0	3.74	13.8	0.17	11.8	64	15	n.a.	24.58	566.98
301	30	0.0	n.v.		n.c.		64	n.a.	n.a.		
302	30	1.6	0.87	12.3	0.09	11.4	64	26	n.a.	16.39	15.12
303	30	2.4	2.09	13.1	0.17	11.4	64	25	n.a.	16.39	34.02
304	30	3.2	2.35	13.1	0.26	11.8	64	23	n.a.	16.39	60.47
305	30	4.8	2.96	13.3	0.61	11.8	64	23	n.a.	16.39	136.07
306	30	6.4	3.39	13.3	1.04	11.8	64	25	25	16.39	241.89
307	30	8.0	3.57	13.3	1.22	11.8	64	23	20	16.39	377.98
308	40	0.0	n.v.		n.c.		64	n.a.	n.a.		
309	40	1.6	0.61	12.3	0.17	12.3	64	37	n.a.	12.29	11.34
310	40	2.4	1.39	12.3	0.79	11.8	64	37	n.a.	12.29	25.51
311	40	3.2	2.00	12.3	1.22	11.8	64	37	37	12.29	45.36
312	40	4.8	2.52	12.3	1.39	11.8	64	37	37	12.29	102.06
313	40	6.4	3.04	12.8	2.00	11.8	64	35	27	12.29	181.43
314	40	8.0	3.22	13.3	2.35	12.3	64	32	22	12.29	283.49
315	50	0.0	n.v.		n.c.		64	n.a.	n.a.		
316	50	1.6	0.17	11.8	n.c.		64	n.a.	n.a.	9.83	9.07
317	50	2.4	0.61	11.8	0.35	12.3	64	43	n.a.	9.83	20.41
318	50	3.2	1.74	11.8	0.96	11.8	64	42	n.a.	9.83	36.29
319	50	4.8	2.61	12.3	1.65	11.8	64	43	32	9.83	81.64

Table 2C (Continued)

Data and Results for Tank with Conical Bottom, $\frac{h_o}{D} = 4.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
320	50	6.4	2.87	12.3	2.17	11.8	64	43	27	9.83	145.15
321	50	8.0	3.22	12.8	2.44	12.3	64	42	27	9.83	226.79
322	60	0.0	n.v.		n.c.		64	n.a.	n.a.		
323	60	1.6	n.v.		n.c.		64	n.a.	n.a.		
324	60	2.4	0.61	11.8	0.35	11.8	64	47	n.a.	8.19	17.01
325	60	3.2	1.04	11.4	0.70	12.3	64	46	n.a.	8.19	30.24
326	60	4.8	1.91	12.3	1.57	12.3	64	46	32	8.19	68.04
327	60	6.4	2.87	12.3	2.09	12.3	64	42	26	8.19	120.96
328	60	8.0	3.13	12.3	2.44	12.3	64	42	26	8.19	189.00
329	70	0.0	n.v.		n.c.		64	n.a.	n.a.		
330	70	1.6	n.v.		n.c.		64	n.a.	n.a.		
331	70	2.4	0.44	11.8	0.17	11.8	64	37	n.a.	7.02	14.58
332	70	3.2	1.30	11.8	0.79	12.3	64	37	n.a.	7.02	25.92
333	70	4.8	1.83	11.4	1.30	12.3	64	50	37	7.02	58.32
334	70	6.4	2.52	11.8	1.83	12.8	64	50	32	7.02	103.68
335	70	8.0	3.04	11.8	2.44	12.8	64	50	27	7.02	161.99
336	80	0.0	n.v.		n.c.		64	n.a.	n.a.		
337	80	1.6	n.v.		n.c.		64	n.a.	n.a.		
338	80	2.4	0.17	11.4	n.c.		64	n.a.	n.a.	6.15	12.76
339	80	3.2	1.04	11.4	0.44	11.8	64	50	n.a.	6.15	22.68
340	80	4.8	1.91	11.4	1.22	12.3	64	50	50	6.15	51.03
341	80	6.4	2.61	11.8	2.00	1.28	64	52	32	6.15	90.72
342	80	8.0	2.87	11.8	2.17	12.8	64	50	30	6.15	141.74
343	90	0.0	n.v.		n.c.		64	n.a.	n.a.		
344	90	1.6	n.v.		n.c.		64	n.a.	n.a.		
345	90	2.4	0.09	11.4	n.c.		64	n.a.	n.a.	5.46	11.34

Table 2C (Concluded)

Data and Results for Tank with Conical Bottom, $\frac{h_o}{D} = 4.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{R1} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
346	90	3.2	0.70	10.9	0.35	12.8	64	60	n.a.	5.46	20.16
347	90	4.8	1.65	11.4	1.04	12.8	64	60	60	5.46	45.36
348	90	6.4	2.44	11.4	1.52	12.8	64	53	37	5.46	79.93
349	90	8.0	2.78	10.9	2.09	12.8	64	60	32	5.46	125.99

Table 3A

Data and Results for Tank with Dished Bottom, $\frac{h_o}{D} = 8.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
350	20	0.0	n.v.		n.c.		62	n.a.	n.a.		
351	20	1.6	0.44	13.3	n.c.		62	n.a.	n.a.	25.34	22.00
352	20	2.4	2.61	13.3	n.c.		62	n.a.	n.a.	25.34	49.50
353	20	3.2	4.44	13.8	n.c.		62	n.a.	n.a.	25.34	88.00
354	20	4.8	5.57	13.8	n.c.		62	n.a.	n.a.	25.34	198.00
355	20	6.4	6.52	13.8	0.09	12.3	62	15	n.a.	25.34	351.99
356	20	8.0	6.78	13.8	0.09	12.3	62	15	n.a.	25.34	549.98
357	30	0.0	n.v.		n.c.		62	n.a.	n.a.		
358	30	1.6	0.35	12.3	0.09	11.8	62	25	n.a.	16.89	14.67
359	30	2.4	1.65	13.3	0.35	12.3	62	25	n.a.	16.89	33.00
360	30	3.2	2.52	13.3	0.44	12.3	62	26	n.a.	16.89	58.66
361	30	4.0	3.65	13.8	0.44	12.3	62	25	n.a.	16.89	91.66
362	30	4.8	4.78	13.8	0.52	12.3	62	25	n.a.	16.89	132.00
363	30	6.4	5.48	13.8	0.70	12.8	62	25	n.a.	16.89	234.64
364	30	8.0	6.26	13.8	0.79	12.8	62	25	n.a.	16.89	366.65
365	40	0.0	n.v.		n.c.		62	n.a.	n.a.		
366	40	1.6	0.26	12.3	n.c.	12.3	62	n.a.	n.a.	12.67	11.00
367	40	2.4	0.96	12.8	0.52	12.3	62	32	n.a.	12.67	24.75
368	40	3.2	1.83	12.8	0.87	12.3	62	33	n.a.	12.67	44.00
369	40	4.0	2.61	13.3	0.96	12.3	62	33	n.a.	12.67	68.75
370	40	4.8	3.91	13.3	1.04	12.3	62	33	33	12.67	99.00
371	40	6.4	5.22	13.8	1.22	12.3	62	33	32	12.67	175.99
372	40	8.0	5.57	13.8	1.48	12.3	62	33	30	12.67	274.99
373	50	0.0	n.v.		n.c.		62	n.a.	n.a.		
374	50	1.6	n.v.		n.c.		62	n.a.	n.a.		
375	50	2.4	0.61	12.3	0.26	12.3	62	26	n.a.	10.14	19.80

Table 3A (Continued)

Data and Results for Tank with Dished Bottom, $\frac{h_o}{D} = 8.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{g\mu} \times 10^{-3}$
376	50	3.2	1.13	12.8	0.52	12.3	62	39	n.a.	10.14	35.20
377	50	4.0	2.35	12.8	1.13	12.3	62	40	40	10.14	55.00
378	50	4.8	3.13	13.3	1.57	12.8	62	41	39	10.14	79.20
379	50	5.6	4.00	13.3	1.91	12.8	62	42	32	10.14	107.80
380	50	6.4	4.70	13.8	2.09	12.8	62	42	32	10.14	140.80
381	50	8.0	4.96	13.3	2.26	12.8	62	42	30	10.14	219.99
382	60	0.0	n.v.		n.c.		62	n.a.	n.a.		
383	60	1.6	n.v.		n.c.		62	n.a.	n.a.		
384	60	2.4	0.09	12.3	n.c.		62	n.a.	n.a.	8.45	16.50
385	60	3.2	0.70	12.8	0.35	12.3	62	53	n.a.	8.45	29.34
386	60	4.0	1.91	12.8	0.87	12.3	62	53	n.a.	8.45	45.84
387	60	4.8	3.04	12.8	1.83	12.3	62	53	45	8.45	66.00
388	60	6.4	4.17	13.3	2.09	12.3	62	57	37	8.45	117.33
389	60	8.0	4.44	13.3	2.35	12.3	62	50	29	8.45	183.33
390	70	0.0	n.v.		n.c.		62	n.a.	n.a.		
391	70	1.6	n.v.		n.c.		62	n.a.	n.a.		
392	70	3.2	0.26	12.3	0.09	11.8	62	57	n.a.	7.24	25.14
393	70	4.0	1.04	12.3	0.44	11.8	62	60	n.a.	7.24	39.29
394	70	4.8	2.00	12.3	1.04	11.8	62	60	60	7.24	56.57
395	70	6.4	3.39	12.3	1.83	12.3	62	60	50	7.24	100.57
396	70	8.0	3.74	12.3	2.00	12.3	62	60	37	7.24	157.14
397	80	0.0	n.v.		n.c.		62	n.a.	n.a.		
398	80	1.6	n.v.		n.c.		62	n.a.	n.a.		
399	80	3.2	0.09	11.4	n.c.		62	n.a.	n.a.	6.34	22.00
400	80	4.0	0.78	11.8	0.35	11.4	62	65	n.a.	6.34	34.37
401	80	4.8	1.74	11.8	0.87	11.4	62	65	n.a.	6.34	49.50

Table 3A (Concluded)

Data and Results for Tank with Dished Bottom, $\frac{h_o}{D} = 8.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
402	80	6.4	3.22	12.3	1.74	11.8	62	60	45	6.34	88.00
403	80	8.0	4.09	12.3	2.35	11.8	62	63	42	6.34	137.50
404	90	0.0	n.v.		n.c.		62	n.a.	n.a.		
405	90	1.6	n.v.		n.c.		62	n.a.	n.a.		
406	90	3.2	0.09	11.4	n.c.		62	n.a.	n.a.	5.63	19.56
407	90	4.0	0.78	11.4	0.26	11.8	62	65	n.a.	5.63	30.56
408	90	4.8	1.57	11.8	0.79	11.8	62	65	n.a.	5.63	44.00
409	90	6.4	2.96	12.3	1.39	11.8	62	65	60	5.63	77.53
410	90	8.0	4.00	12.8	2.00	11.8	62	65	53	5.63	122.22

Table 3B

Data and Results for Tank with Dished Bottom, $\frac{h_o}{D} = 6.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
411	20	0.0	n.v.		n.c.		62	n.a.	n.a.		
412	20	1.6	1.39	13.3	n.c.		62	n.a.	n.a.	25.34	22.00
413	20	2.4	3.04	13.3	0.09	12.3	62	17	n.a.	25.34	49.50
414	20	3.2	3.83	13.8	0.09	12.3	62	17	n.a.	25.34	88.00
415	20	4.8	4.70	13.8	0.17	12.8	62	14	n.a.	25.34	198.00
416	20	6.4	5.13	13.8	0.26	12.8	62	17	n.a.	25.34	351.99
417	20	8.0	5.48	13.8	0.35	12.8	62	17	n.a.	25.34	549.98
418	30	0.0	n.v.		n.c.		62	n.a.	n.a.	16.89	0.00
419	30	1.6	0.78	12.8	0.26	12.3	62	23	n.a.	16.89	14.67
420	30	2.4	2.09	12.8	0.44	12.3	62	23	n.a.	16.89	33.00
421	30	3.2	3.13	13.3	0.61	12.3	62	24	n.a.	16.89	58.66
422	30	4.0	3.91	13.3	0.70	12.3	62	26	n.a.	16.89	91.66
423	30	4.8	4.35	13.3	0.79	12.3	62	23	n.a.	16.89	132.00
424	30	6.4	4.95	13.8	0.87	12.8	62	26	n.a.	16.89	234.64
425	30	8.0	5.22	13.8	0.96	12.3	62	25	n.a.	16.89	366.65
426	40	0.0	n.v.		n.c.		62	n.a.	n.a.		
427	40	1.6	0.26	12.3	n.c.		62	n.a.	n.a.	12.67	11.00
428	40	2.4	1.13	12.3	0.70	11.8	62	31	n.a.	12.67	24.75
429	40	3.2	2.26	12.8	1.22	11.8	62	33	33	12.67	44.00
430	40	4.8	3.65	12.8	1.39	11.4	62	33	30	12.67	99.00
431	40	6.4	4.26	12.8	1.91	11.8	62	33	28	12.67	175.99
432	40	8.0	4.87	13.3	2.09	11.8	62	34	25	12.67	274.99
433	50	0.0	n.v.		n.c.		62	n.a.	n.a.		
434	50	1.6	0.09	11.8	n.c.		62	n.a.	n.a.	10.14	8.80
435	50	2.4	0.70	11.8	0.44	12.3	62	41	n.a.	10.14	19.80
436	50	3.2	2.09	11.8	0.87	12.3	62	40	n.a.	10.14	35.20

Table 3B (Continued)

Data and Results for Tank with Dished Bottom, $\frac{h_o}{D}$ = 6.0, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
437	50	4.0	2.78	11.8	1.48	12.3	62	43	33	10.14	55.00
438	50	4.8	3.39	11.8	1.91	12.3	62	42	30	10.14	79.20
439	50	6.4	4.35	11.8	2.61	12.3	62	43	28	10.14	140.00
440	50	8.0	4.78	12.3	3.22	12.8	62	43	25	10.14	219.99
441	60	0.0	n.v.		n.c.		62	n.a.	n.a.		
442	60	1.6	0.09	11.8	n.c.		62	n.a.	n.a.	8.45	7.33
443	60	2.4	0.44	11.4	0.17	12.8	62	49	n.a.	8.45	16.50
444	60	3.2	1.57	11.8	0.79	12.8	62	52	n.a.	8.45	29.34
445	60	4.0	2.35	12.3	1.30	12.8	62	49	37	8.45	45.84
446	60	4.8	3.22	12.3	1.83	12.8	62	51	34	8.45	66.00
447	60	6.4	4.17	12.8	2.61	12.8	62	51	27	8.45	117.33
448	60	8.0	4.52	12.8	3.22	13.3	62	52	27	8.45	183.33
449	70	0.0	n.v.		n.c.		62	n.a.	n.a.		
450	70	1.6	n.v.		n.c.		62	n.a.	n.a.		
451	70	3.2	0.78	11.4	0.44	11.8	62	50	n.a.	7.24	25.14
452	70	4.0	1.83	11.8	0.96	11.8	62	50	n.a.	7.24	39.29
453	70	4.8	2.70	11.8	1.57	11.8	62	50	33	7.24	56.57
454	70	6.4	3.91	12.3	2.52	12.3	62	46	30	7.24	100.57
455	70	8.0	4.17	12.8	2.87	12.8	62	54	17	7.24	157.14
456	80	0.0	n.v.		n.c.		62	n.a.	n.a.		
457	80	1.6	n.v.		n.c.		62	n.a.	n.a.		
458	80	3.2	0.96	11.4	0.44	11.8	62	70	n.a.	6.34	22.00
459	80	4.0	1.22	11.4	0.96	11.8	62	61	n.a.	6.34	34.37
460	80	4.8	2.44	11.8	1.13	12.3	62	61	60	6.34	49.50
461	80	6.4	3.30	11.8	2.09	12.3	62	60	36	6.34	88.00
462	80	8.0	4.09	12.3	2.87	12.8	62	59	34	6.34	137.50

Table 3B (Concluded)

Data and Results for Tank with Dished Bottom, $\frac{h_o}{D} = 6.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
463	90	0.0	n.v.		n.c.		63	n.a.	n.a.		
464	90	1.6	n.v.		n.c.		63	n.a.	n.a.		
465	90	2.4	0.09	11.4	0.09	11.4	63	65	n.a.	5.55	11.17
466	90	3.2	0.44	11.4	0.17	11.4	63	65	n.a.	5.55	19.86
467	90	4.0	1.13	11.4	0.52	12.3	63	64	n.a.	5.55	31.03
468	90	4.8	2.17	11.4	1.04	12.3	63	66	66	5.55	44.68
469	90	6.4	3.04	11.8	1.74	12.3	63	68	37	5.55	79.43
470	90	8.0	4.00	11.8	2.61	12.3	63	70	35	5.55	124.11

Table 3C

Data and Results for Tank with Dished Bottom, $\frac{h_o}{D} = 4.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
471	20	0.0	n.v.		n.c.		63	n.a.	n.a.		
472	20	1.6	1.83	12.8	0.09	11.8	63	15	n.a.	24.95	22.34
473	20	2.4	2.44	12.8	0.17	11.8	63	15	n.a.	24.95	50.26
474	20	3.2	2.87	12.8	0.35	11.8	63	16	n.a.	24.95	89.36
475	20	4.8	3.39	13.3	0.61	11.8	63	16	n.a.	24.95	201.06
476	20	6.4	3.57	13.3	0.70	11.8	63	17	n.a.	24.95	351.43
477	20	8.0	3.74	13.3	1.04	11.8	63	17	17	24.95	558.50
478	30	0.0	n.v.		n.c.		63	n.a.	n.a.		
479	30	1.6	1.13	12.8	0.35	11.8	63	23	n.a.	16.63	14.89
480	30	2.4	2.00	12.8	0.70	11.8	63	23	n.a.	16.63	33.51
481	30	3.2	2.44	12.8	0.96	11.8	63	23	n.a.	16.63	59.57
482	30	4.8	3.04	12.8	1.13	11.8	63	25	25	16.63	134.04
483	30	6.4	3.30	13.3	1.52	11.8	63	25	22	16.63	238.27
484	30	8.0	3.57	13.3	2.00	11.8	63	26	17	16.63	372.32
485	40	0.0	n.v.		n.c.		63	n.a.	n.a.		
486	40	1.6	0.52	12.3	0.26	11.8	63	22	n.a.	12.48	11.17
487	40	2.4	1.30	12.3	0.87	11.8	63	26	n.a.	12.48	25.13
488	40	3.2	2.17	12.8	1.30	11.8	63	30	30	12.48	44.68
489	40	4.8	2.96	12.8	1.91	11.8	63	32	26	12.48	100.53
490	40	6.4	3.48	13.3	2.35	12.3	63	34	22	12.48	178.72
491	40	8.0	3.57	13.3	2.61	12.3	63	34	20	12.48	279.25
492	50	0.0	n.v.		n.c.		63	n.a.	n.a.		
493	50	1.6	0.26	11.8	0.17	11.8	63	25	n.a.	9.98	8.94
494	50	2.4	0.87	12.3	0.61	11.8	63	32	n.a.	9.98	20.11
495	50	3.2	1.83	12.8	1.13	12.3	63	37	37	9.98	35.74
496	50	4.8	2.96	12.8	2.00	12.3	63	37	26	9.98	80.42

Table 3C (Continued)

Data and Results for Tank with Dished Bottom, $\frac{h_o}{D} = 4.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
497	50	6.4	3.13	12.8	2.44	12.8	63	47	22	9.98	142.97
498	50	8.0	3.39	12.8	2.70	12.8	63	41	20	9.98	223.40
499	60	0.0	n.v.		n.c.		63	n.a.	n.a.		
500	60	1.6	0.17	11.8	0.09	11.8	63	24	n.a.	8.32	7.45
501	60	2.4	0.61	11.8	0.44	11.8	63	26	n.a.	8.32	16.75
502	60	3.2	1.48	11.8	0.79	11.8	63	30	n.a.	8.32	29.79
503	60	4.8	2.52	11.8	1.04	11.8	63	32	26	8.32	67.02
504	60	6.4	2.96	12.8	1.74	12.3	63	32	22	8.32	119.15
505	60	8.0	3.30	12.8	2.61	12.3	63	38	20	8.32	186.17
506	70	0.0	n.v.		n.c.		63	n.a.	n.a.		
507	70	1.6	0.09	11.8	n.c.		63	n.a.	n.a.	7.13	6.38
508	70	2.4	0.44	11.4	0.26	11.4	63	37	n.a.	7.13	14.36
509	70	3.2	1.13	11.8	0.79	11.8	63	37	n.a.	7.13	25.53
510	70	4.8	2.17	12.3	1.65	12.3	63	45	26	7.13	57.44
511	70	6.4	3.04	12.3	2.26	12.3	63	50	22	7.13	102.12
512	70	8.0	3.13	12.3	2.61	12.3	63	52	22	7.13	159.57
513	80	0.0	n.v.		n.c.		63	n.a.	n.a.		
514	80	1.6	n.v.		n.c.		63	n.a.	n.a.		
515	80	2.4	0.26	11.4	0.17	11.8	63	53	n.a.	6.24	12.57
516	80	3.2	0.78	11.8	0.61	11.8	63	57	n.a.	6.24	22.34
517	80	4.8	2.09	11.8	1.48	11.8	63	57	29	6.24	50.26
518	80	6.4	2.96	11.8	2.09	11.8	63	58	24	6.24	89.36
519	80	8.0	3.04	11.8	2.44	12.3	63	58	26	6.24	139.62
520	90	0.0	n.v.		n.c.		63	n.a.	n.a.		
521	90	1.6	n.v.		n.c.		63	n.a.	n.a.		
522	90	2.4	0.26	10.9	0.17	10.4	63	60	n.a.	5.55	11.17

Table 3C (Concluded)

Data and Results for Tank with Dished Bottom, $\frac{h_o}{D} = 4.0$, D = 11.5 inches

Run No.	Q_T (GPM)	Q_C (GPM)	$\frac{h_f}{D}$	P_f (psia)	$\frac{h_c}{D}$	P_c (psia)	T_L (^oF)	Q_{Rc} (GPM)	Q_{Rl} (GPM)	$\frac{D\mu}{\rho q} \times 10^5$	$\frac{T}{q\mu} \times 10^{-3}$
523	90	3.2	0.78	10.9	0.44	10.9	63	60	n.a.	5.55	19.86
524	90	4.8	1.83	11.4	1.22	12.3	63	60	54	5.55	44.68
525	90	6.4	2.61	11.8	1.91	12.3	63	63	26	5.55	79.43
526	90	8.0	2.87	11.8	2.26	12.3	63	60	24	5.55	124.11

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